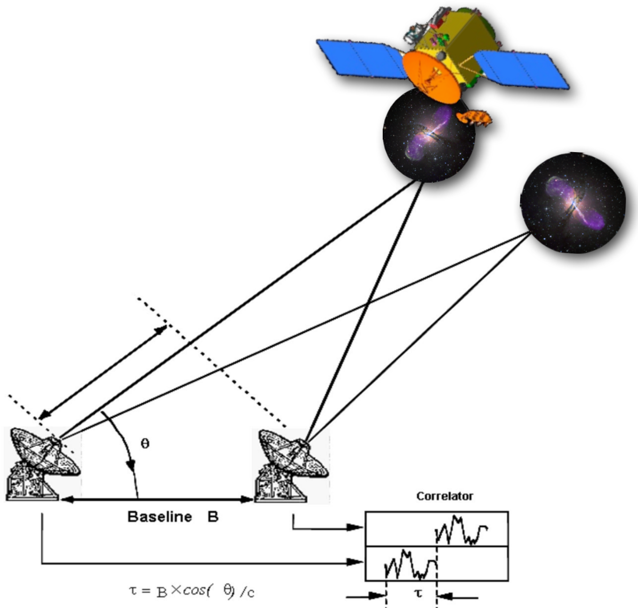
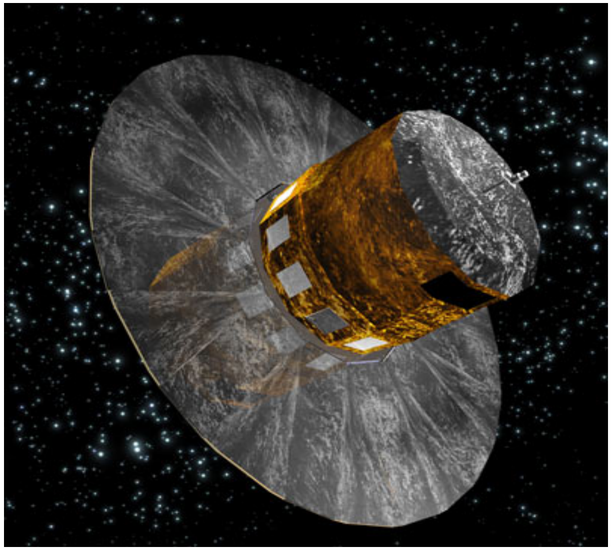
USNO, Washington D.C., 27 July 2017

Comparing multiple Radio wavelength Celestial Frames and the Gaia Optical Frame

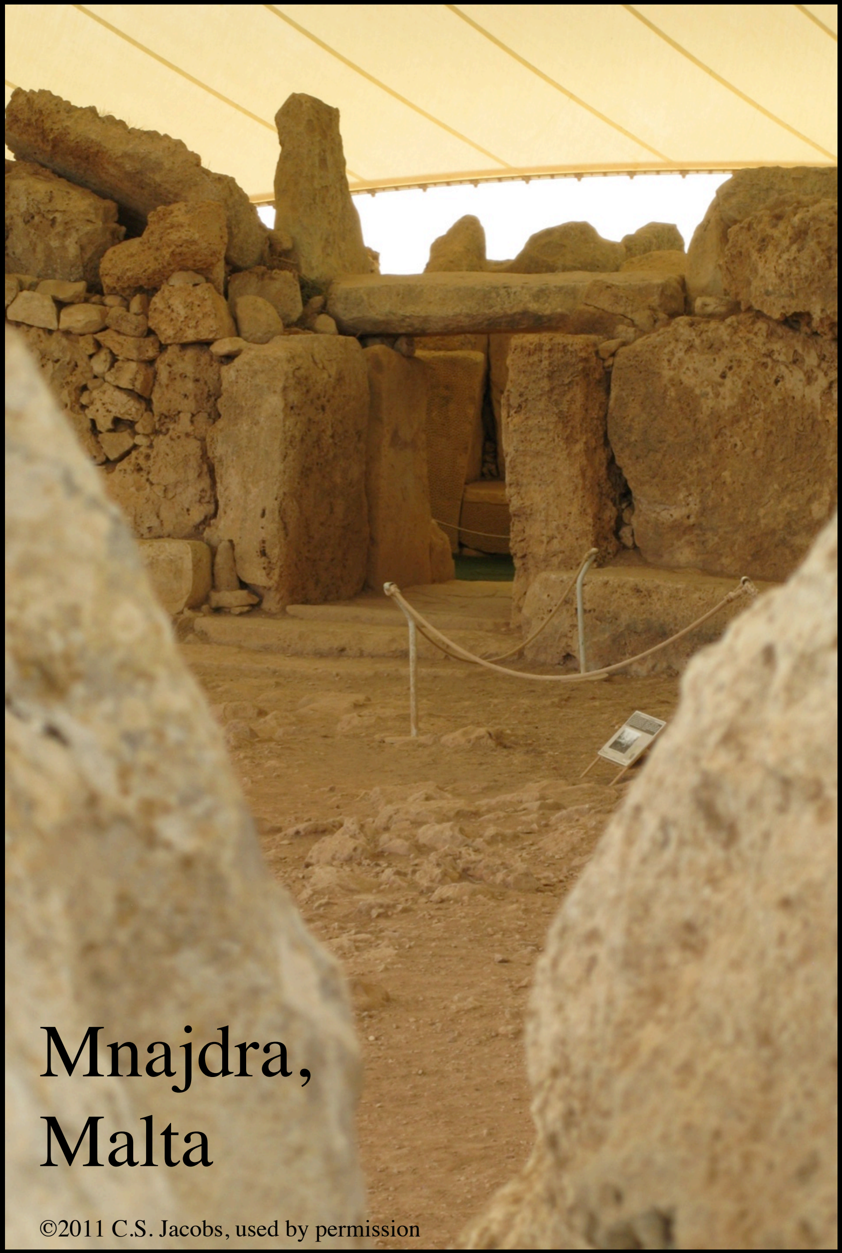




Christopher S. Jacobs, *Jet Propulsion Laboratory, California Institute of Technology*

A. De Witt, A. Bertarini, C. Garcia-Miro, D. Gordon, S. Horiuchi, J. Lovell, J. McCallum, M. Mercolino, J. Quick, L. Snedeker, G. Bourda, P. Charlot.

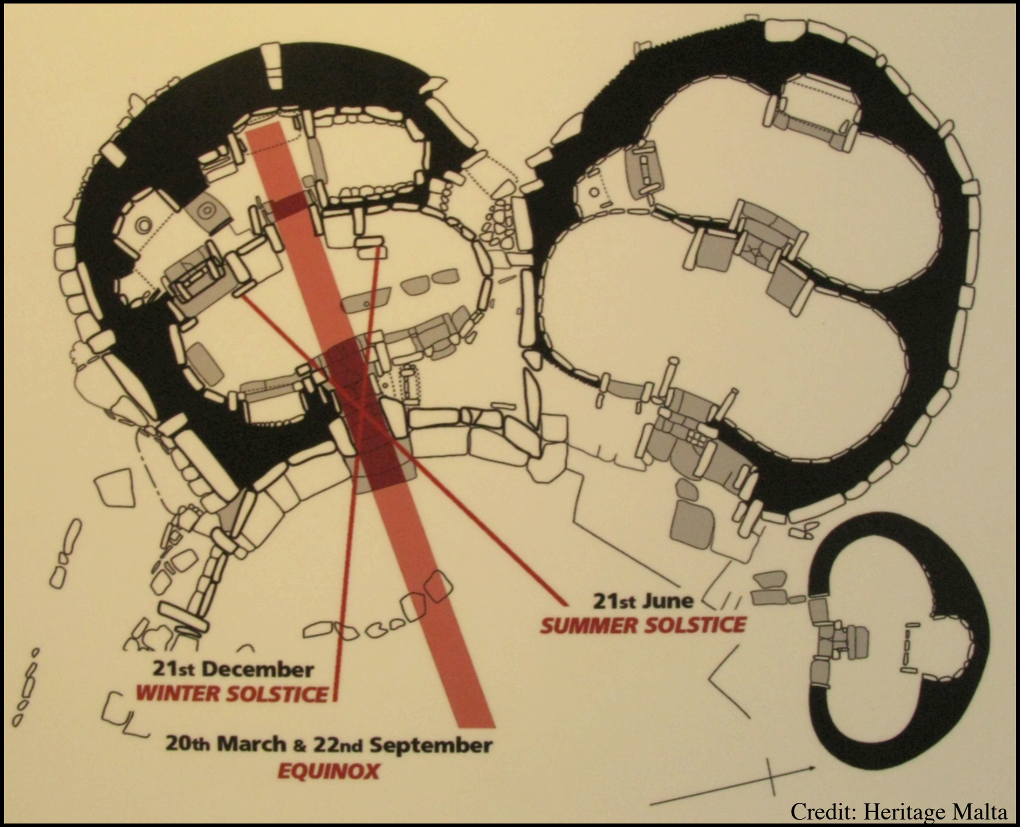
Astrometry: measures positions in the sky, 5000+ years history!



Island of Malta
Ggantija ~3500 B.C.
Mnajdra ~3200 B.C.

Credit: Heritage Malta

Mnajdra solar alignments



Credit: Heritage Malta

Overview: Optical vs. Radio Celestial Frames

- Optical Frames: Used stars up through FK5 (Fricke+, 1988). Proper motions an issue. Hipparcos (Perryman+, 1997) had 100K stars mas precision but mas/yr PM precision. In late 1980s, early 1990s IAU started a move to quasars to leverage zero parallax & PM

- VLBI at SX (8 GHz, 3.6cm) has been only sub-mas frame until last 10 years (e.g. *Ma+, ICRF1, 1998, Ma+, ICRF2, 2009*)
- K-band (24 GHz, 1.2cm) now sub-mas (*Lanyi+, 2010; de Witt+, 2016, 2017*)

- X/Ka (32 GHz, 9mm) also sub-mas (*Jacobs+, 2016, 2017*)

- Gaia optical: data release #1 is sub-mas for auxiliary quasar solution (*Prusti+, 2017*)

- Precision is excellent allowing 3-D rotational alignment precision of 10 to 20 μas

- Accuracy limited by VLBI systematics due to weak southern geometry, troposphere, etc. at few 100 μas

- Gaia precision limited to ~ 500 μas by short span of data in DR#1.

What objects can we use?

Methods for Tying Optical and Radio Celestial Frames

- Need common objects well measured in both optical and radio

- **Radio stars:** Previous generation used galactic stars that emit in radio,

  Crude by today's standards: difficult to achieve desired accuracy level.

  e.g. Lestrade et al. (1995) used radio stars to tie Hipaarcos & VLBI.

- **Thermal emission from regular stars:**

  350 GHz astrometry using Atacama Large Millimeter Array (ALMA)

  Fomalont et al. (pilot observations)

  Verifies bright end of optical, but likely limited to 500 – 1000 μas (2.5 to 5 ppb).

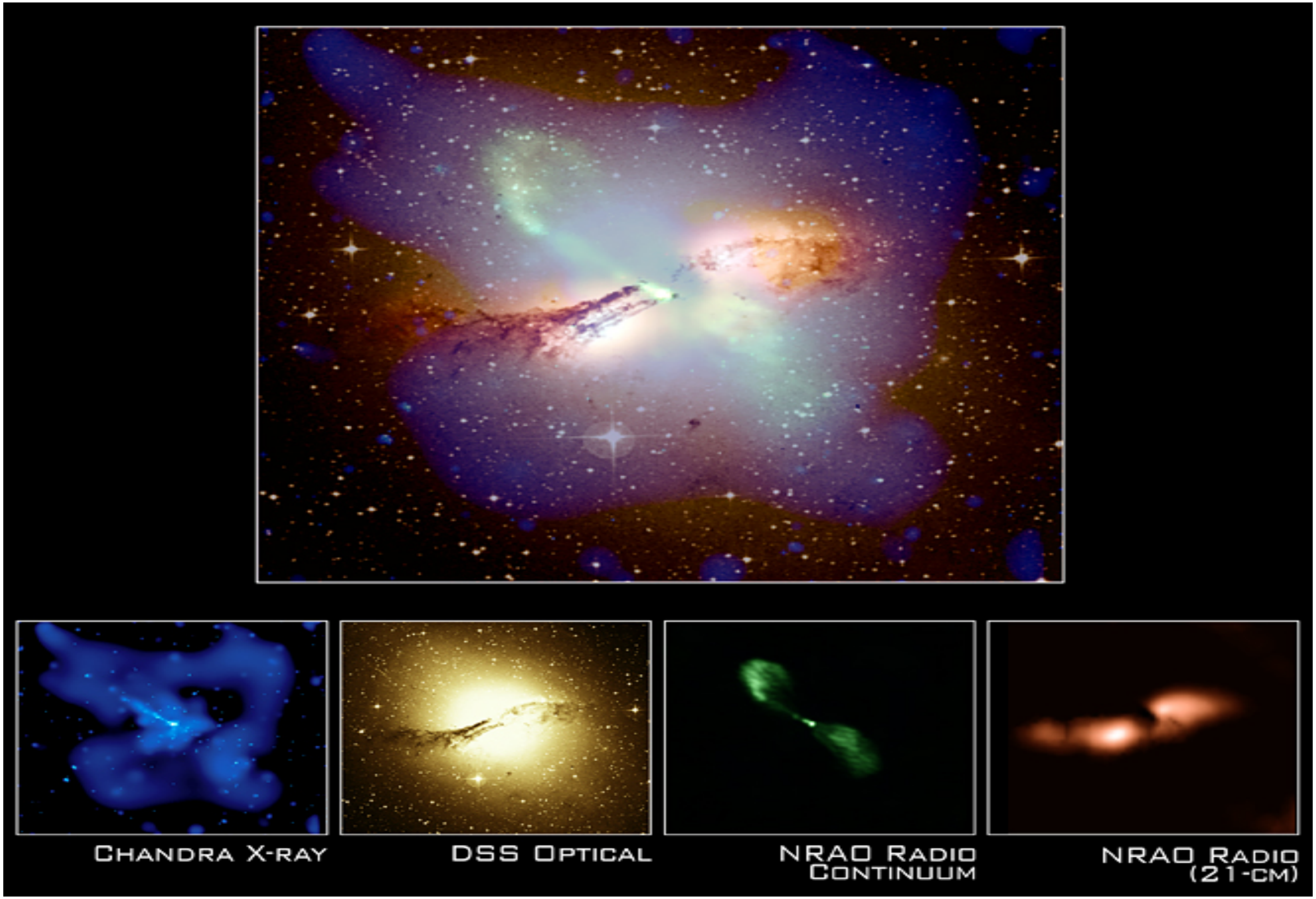
- **Extra-galactic Quasars:** detectable in both radio and optical

  potential for better than 100 μas to 20 μas (0.5 to 0.1 ppb).

  Strengths: extreme distances (> 1 billion light years) means no parallax or proper motion

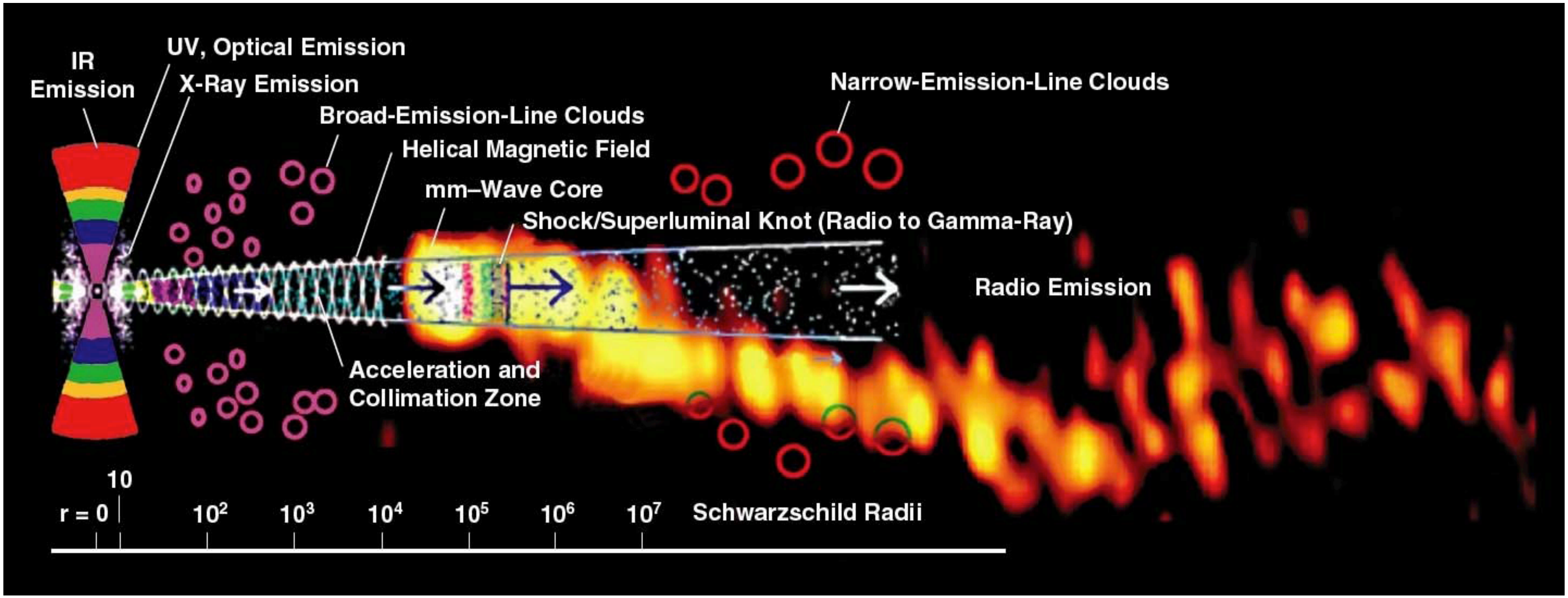
The Source Objects

Example Extragalactic Source: Centaurus-A in X-ray, Optical, Radio



Credits: X-ray (NASA/CXC/M. Karovska et al.); Radio 21-cm image (NRAO/VLA/Schiminovich, et al.),
Radio continuum image (NRAO/VLA/J.Condon et al.); Optical (Digitized Sky Survey U.K. Schmidt Image/STScI)

Active Galactic Nuclei (*Marscher*)



R~0.1-1 μas 1mas

Features of AGN: *Note the Logarithmic length scale*.

"Shock waves are frequency stratified, with highest synchrotron frequencies emitted only close to the shock front where electrons are energized. The part of the jet interior to the mm-wave core is opaque at cm wavelengths. At this point, it is not clear whether substantial emission occurs between the base of the jet and the mm-wave core."

Credits: Alan Marscher, `Relativistic Jets in Active Galactic Nuclei and their relationship to the Central Engine,' Proc. of Science,VI Microquasar Workshop: Microquasars & Beyond, Societa del Casino, Como, Italy, 18-22 Sep 2006. Overlay (not to scale): 3 mm radio image of the blazar 3C454.3 (Krichbaum et al. 1999)

Optical vs. Radio positions

Positions differences from:

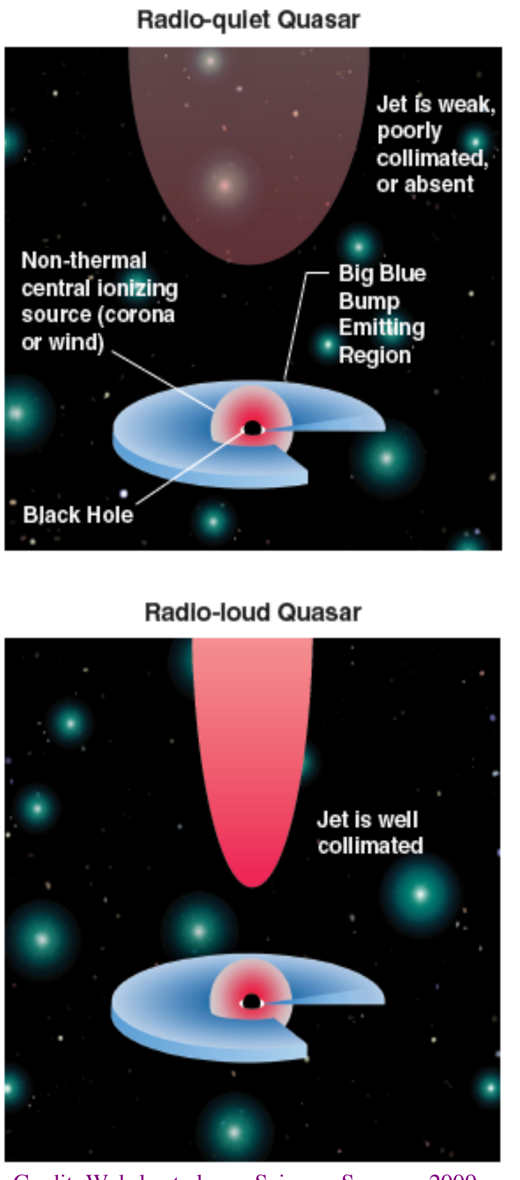
• Astrophysics of emission centroids

- radio: synchrotron from jet

- optical: synchrotron from jet?
  non-thermal ionization from corona?
  big blue bump from accretion disk?

• Instrumental errors both radio & optical

• Analysis errors

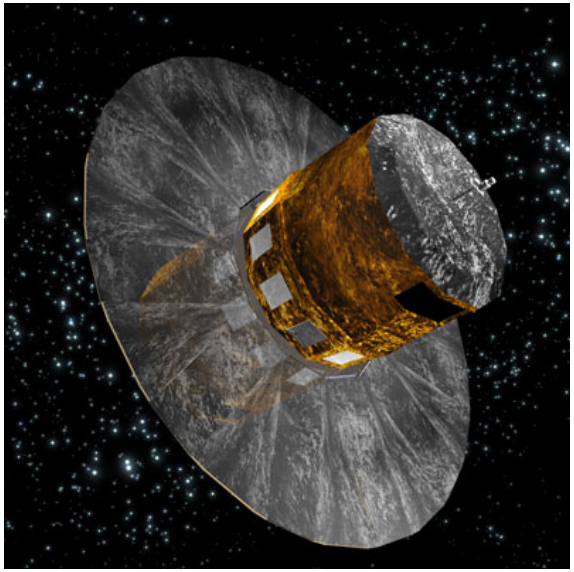


Credit: Wehrle et al, μas Science, Socorro, 2009
http://adsabs.harvard.edu/abs/2009astro2010S.310W

The Gaia Optical Frame

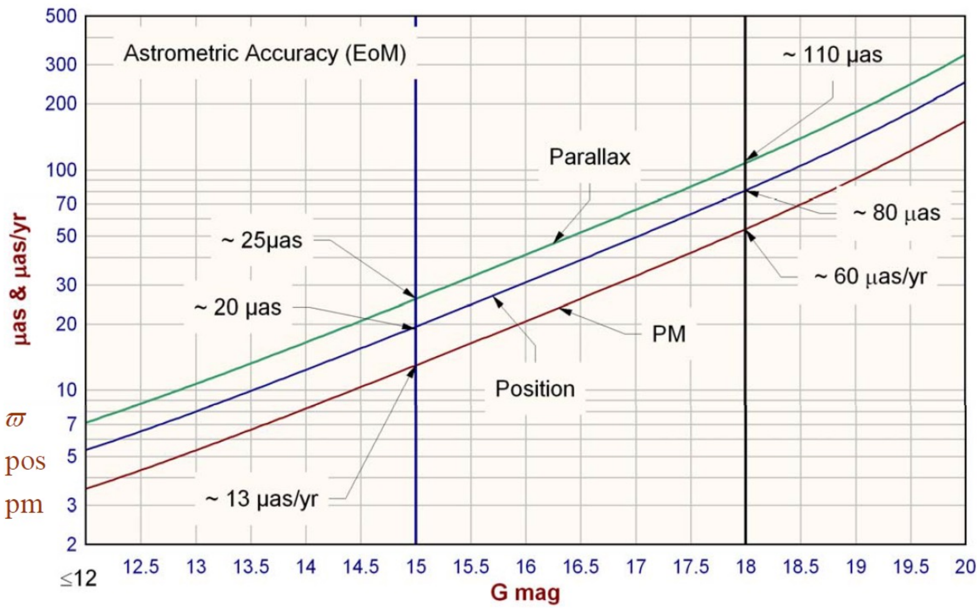
ESA's Gaia optical Astrometry

- Method: extremely accurate centroid of 60 mas pixels. Compare to VLBI sub-mas beam.
- **Astrometry & photometric survey to V = 20.7^{mag}**
  - ~10^9 objects: stars, QSOs, solar system, galaxies.
- **Gaia Celestial Reference Frame (GCRF):**
  - Optically bright objects (V< 18mag) give best precision
  - 1st release Gaia astrometric catalog DR1 Sep 2016,
  - DR2 Apr 2018.



Credit: F. Mignard (2013)

Anticipated precision of Gaia catalogue



Gaia Data Release-1:

~0.3 mas in positions and parallaxes for 2 million brightest stars

~10 mas for rest of the stars

~ 0.5 mas for ICRF2 quasars (auxiliary solution)

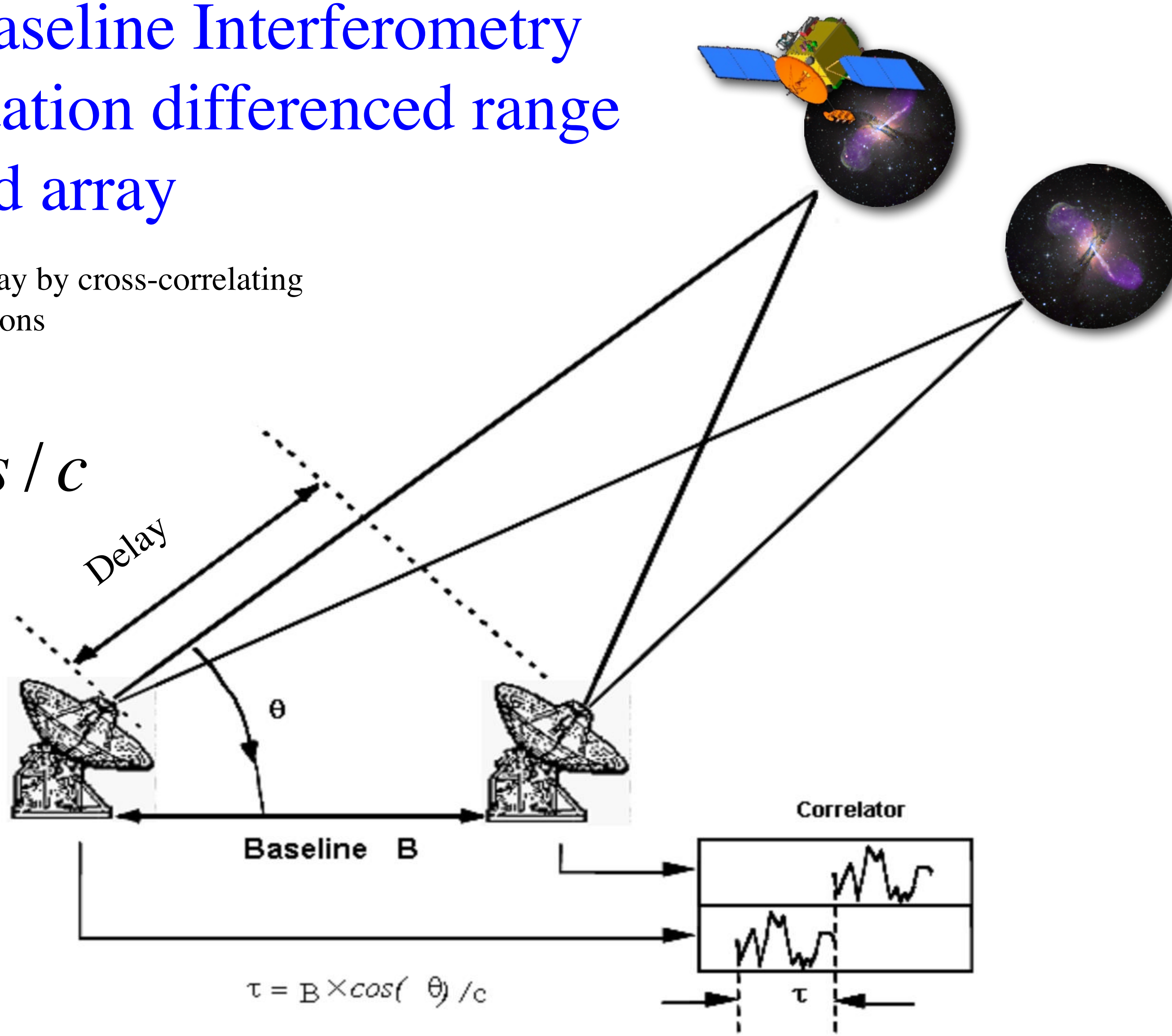
Celestial Frames
using
Radio Interferometry
(VLBI)

Radio Interferometry: Long distance phased arrays

Very Long Baseline Interferometry is a type of station differenced range from a phased array

- Measures geometric delay by cross-correlating signal from two (2) stations

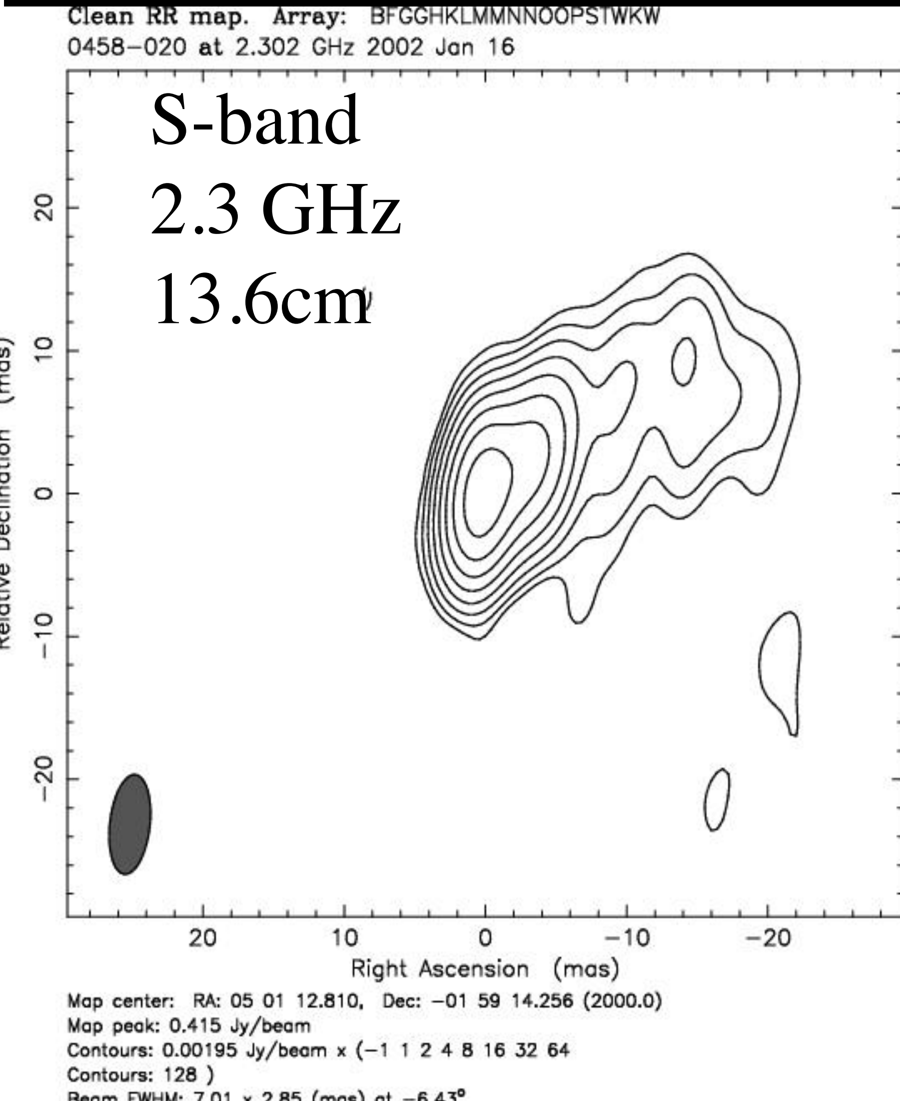
$$\tau = B \bullet s / c$$



10,000 km baselines give resolution of λ/B ~ few nanoradian sub-mas beam !!

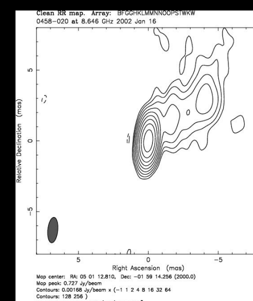
Resolves away all but galactic nucleus

Radio Source Structure vs. Frequency

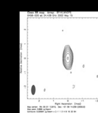


S-band
2.3 GHz
13.6cm

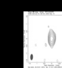
X-band
8.6 GHz
3.6cm



K-band
24 GHz
1.2cm



Q-band
43 GHz
0.7cm

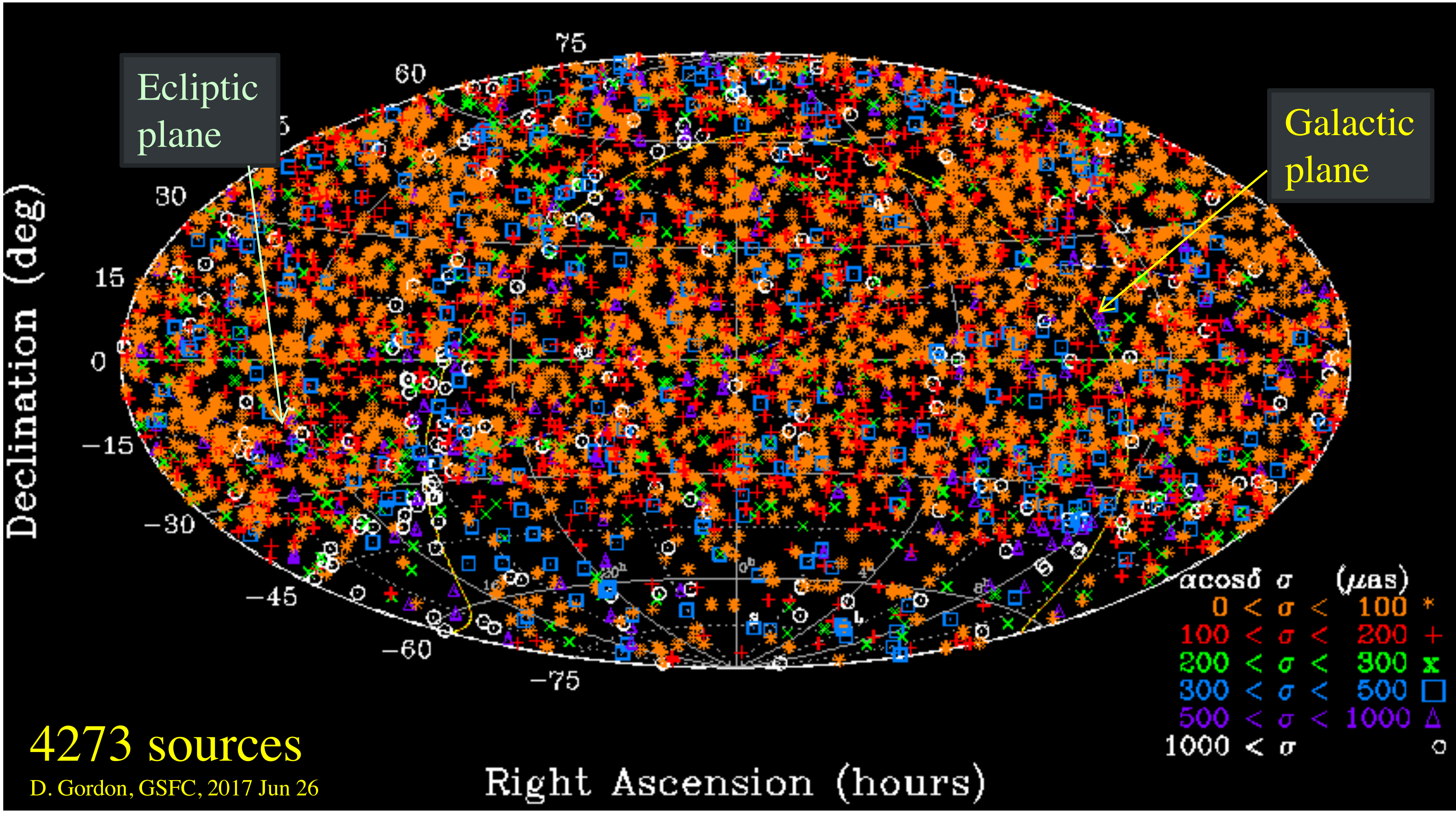


Ka-band
32 GHz
0.9cm

The sources become better →
Less structure

Images credit: Pushkarev & Kovalev A&A, 544, 2012 (SX); Charlot et al, AJ, 139, 2010 (KQ)

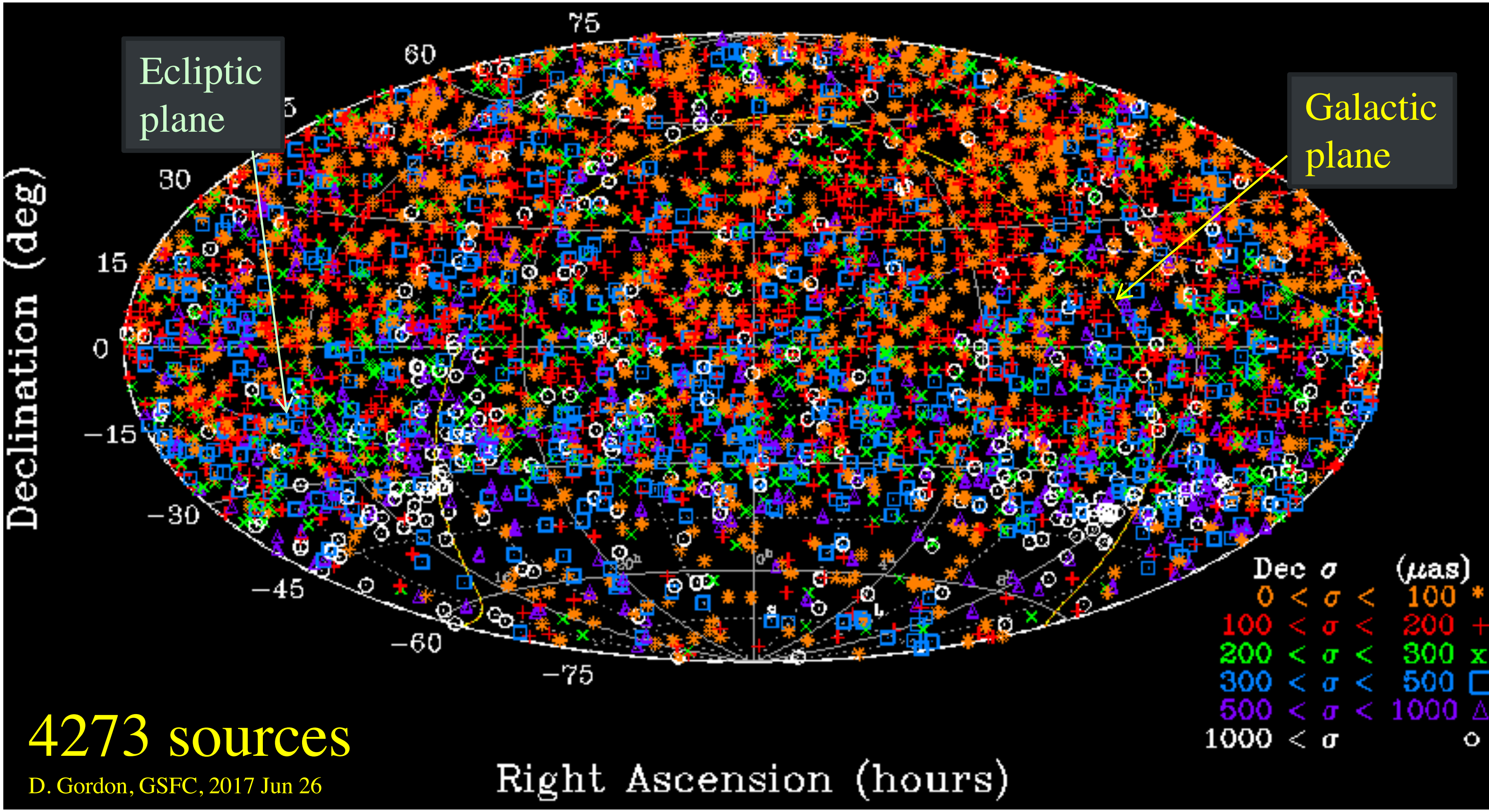
SX (8.4 GHz, 3.6cm) *VLBA+~ 100 other IVS*



- Strengths:
  - 4273 sources
  - Excellent coverage North of δ -30 deg
  - median precision < 50 μas
  - SX's 12 million observations, 40 years
  - over 100 stations contributed

- Weaknesses:
  - Poor coverage south of δ -40 deg
  - only 20% of sources in > 10 sessions
  - source structure worse than K or XKa.

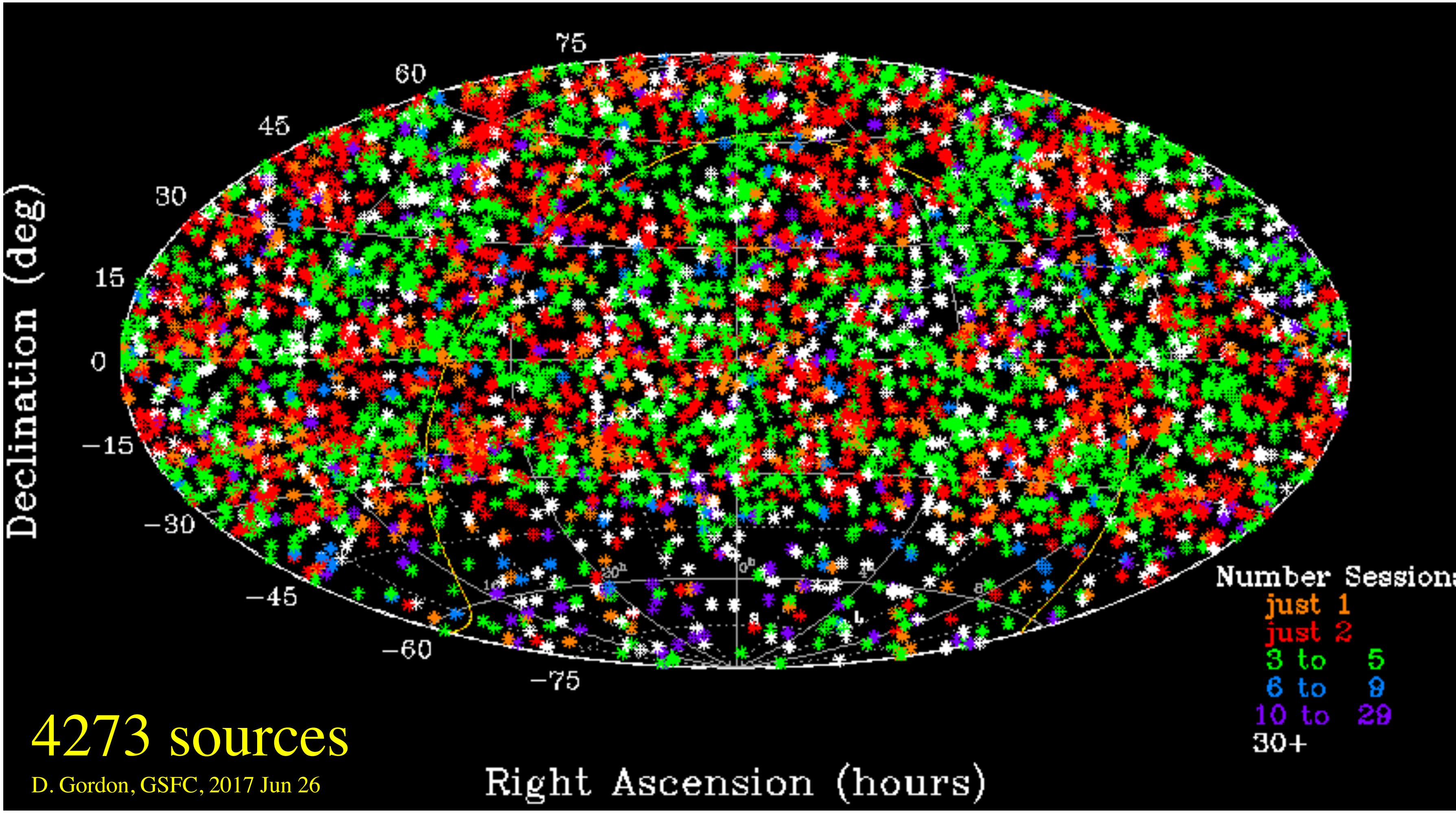
SX (8.4 GHz, 3.6cm): Dec precision weaker than RA



• Strengths:
- 4273 sources
- Excellent coverage North of δ -30 deg
- median precision < 50 μas
- SX's 12 million observations, 40 years
- over 100 stations contributed

• Weaknesses:
- Poor coverage south of δ -40 deg
- only 20% of sources in > 10 sessions
- source structure worse than K or XKa.

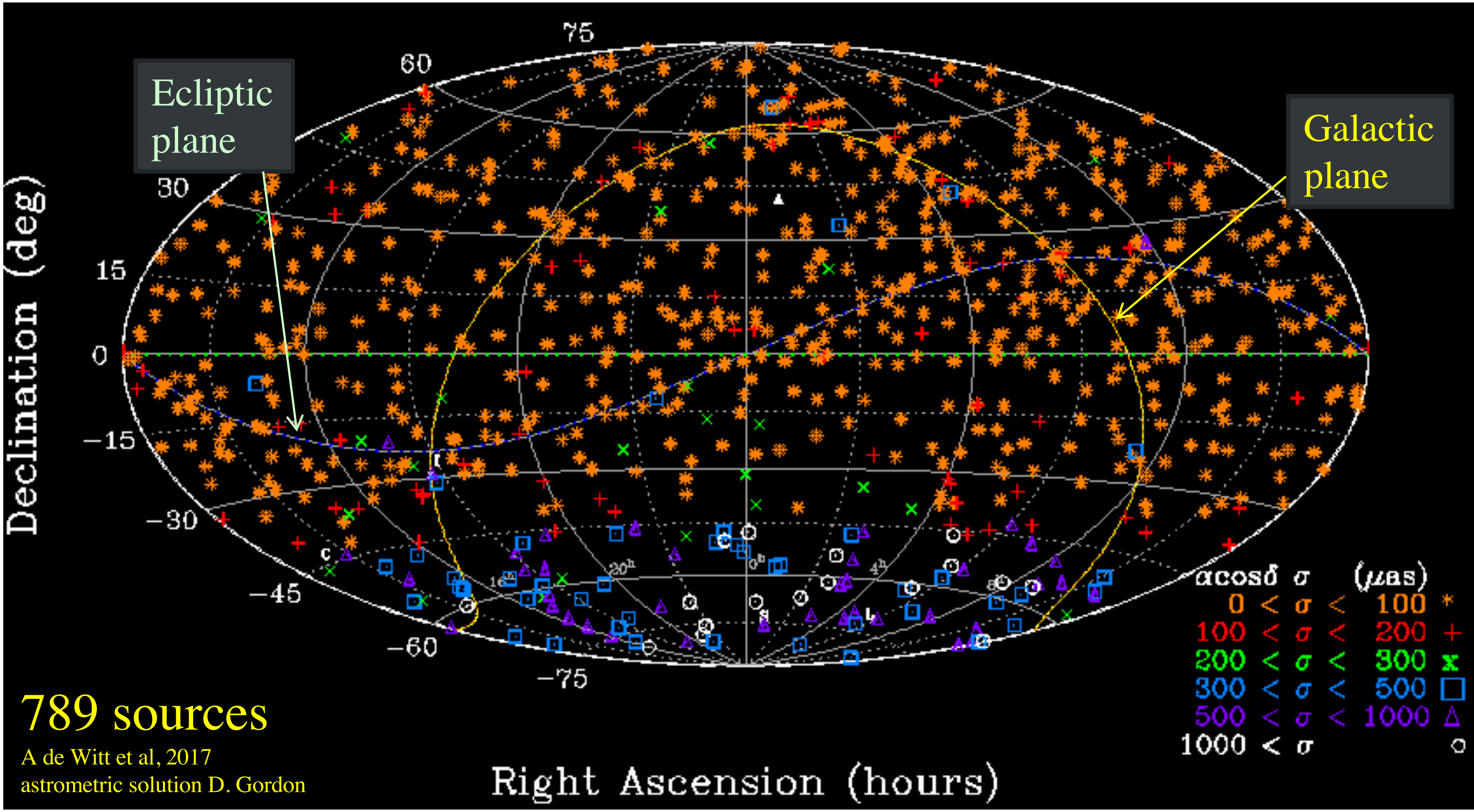
SX: Number Sessions, ~800 > 10 sessions, rest 2-5 survey sessions



- Strengths:
  - 4273 sources
  - Excellent coverage North of δ -30 deg
  - median precision < 50 μas
  - SX's 12 million observations, 40 years
  - over 100 stations contributed

- Weaknesses:
  - Poor coverage south of δ -40 deg
  - only 20% of sources in > 10 sessions
  - source structure worse than K or XKa.

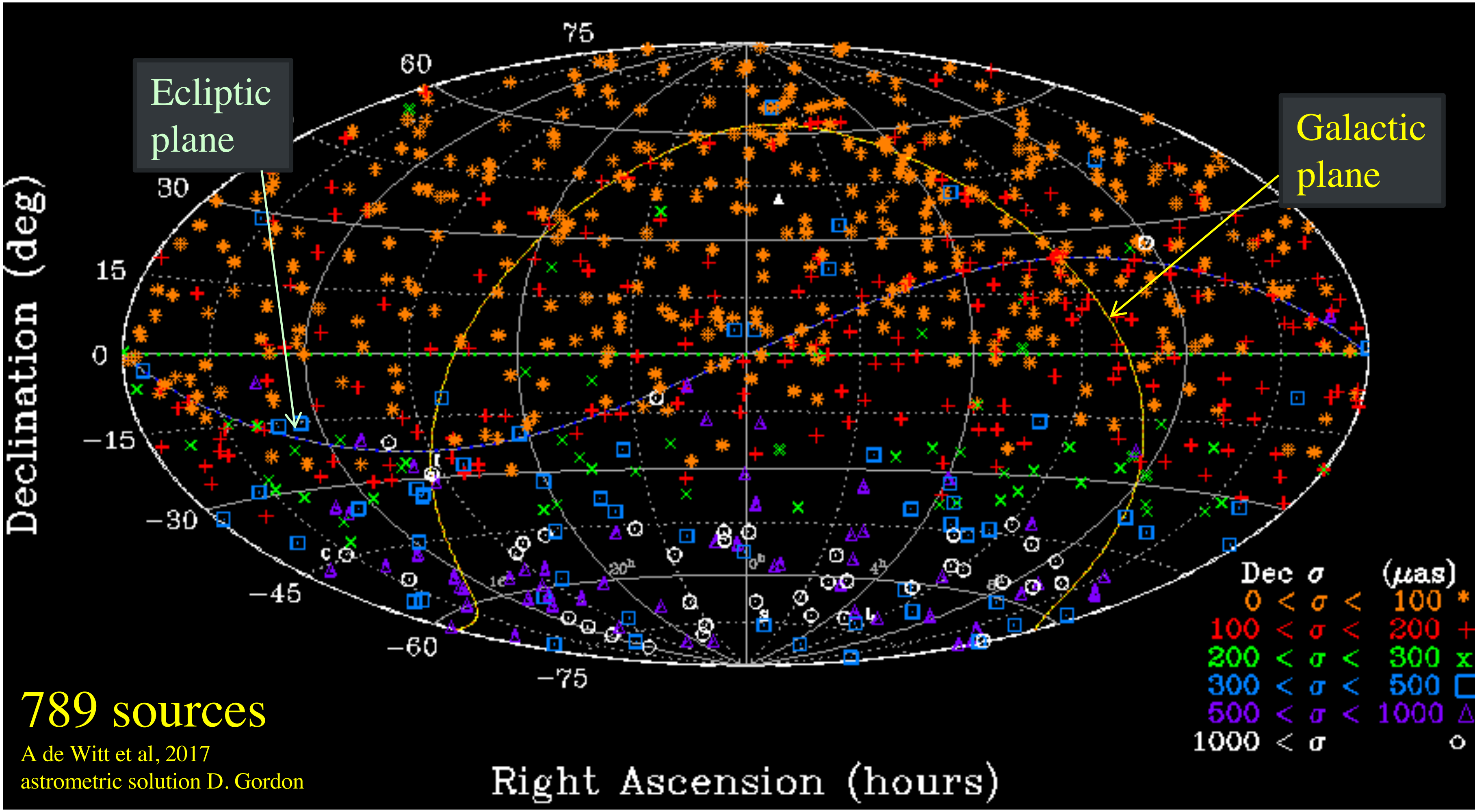
K (24 GHz, 1.2cm) *VLBA+ (S. Africa-Tasmania)*



- Strengths: - Uniform spatial density
  - Galactic plane sources (Petrov+ 2006)
  - less structure than S/X (3.6cm)
  - precision < 100 μas
  - needed ~ 0.25 million observations vs. SX's 12 million!

- Weaknesses:
  - Ionosphere only partially calibrated by GPS.
  - No solar plasma calibrations
  - South (δ < -30 deg) weak due to limited HartRAO, South Africa to Hobart, Tasmania data

K (24 GHz, 1.2cm): Dec precision weaker than RA

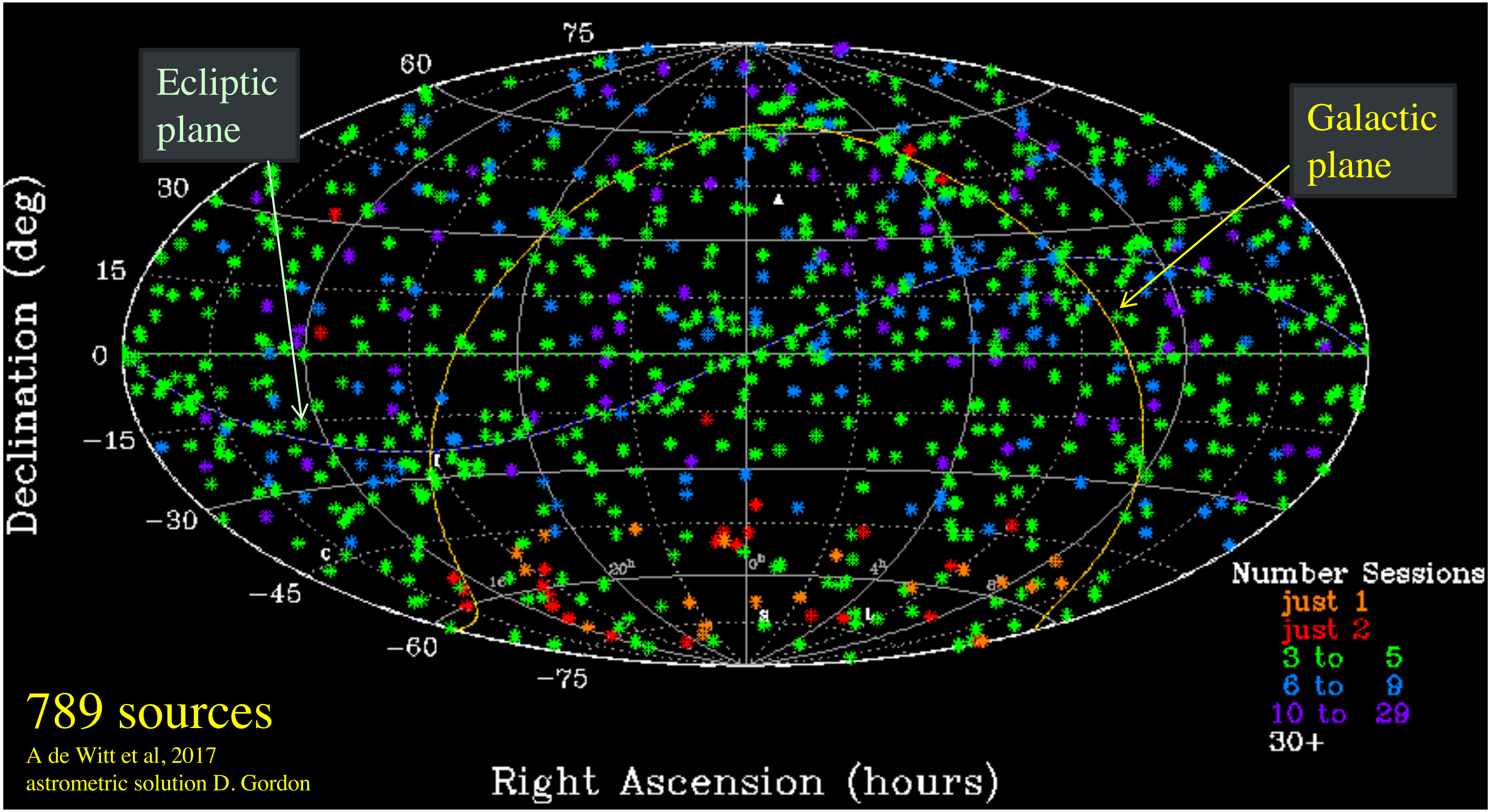


789 sources
A de Witt et al, 2017
astrometric solution D. Gordon

- Strengths:
  - Uniform spatial density
  - Galactic plane sources (Petrov+ 2006)
  - less structure than S/X (3.6cm)
  - precision < 100 μas
  - needed ~ 0.25 million observations vs. SX's 12 million!

- Weaknesses:
  - Ionosphere only partially calibrated by GPS.
  - No solar plasma calibrations
  - South (δ < -30 deg) weak due to limited HartRAO, South Africa to Hobart, Tasmania data

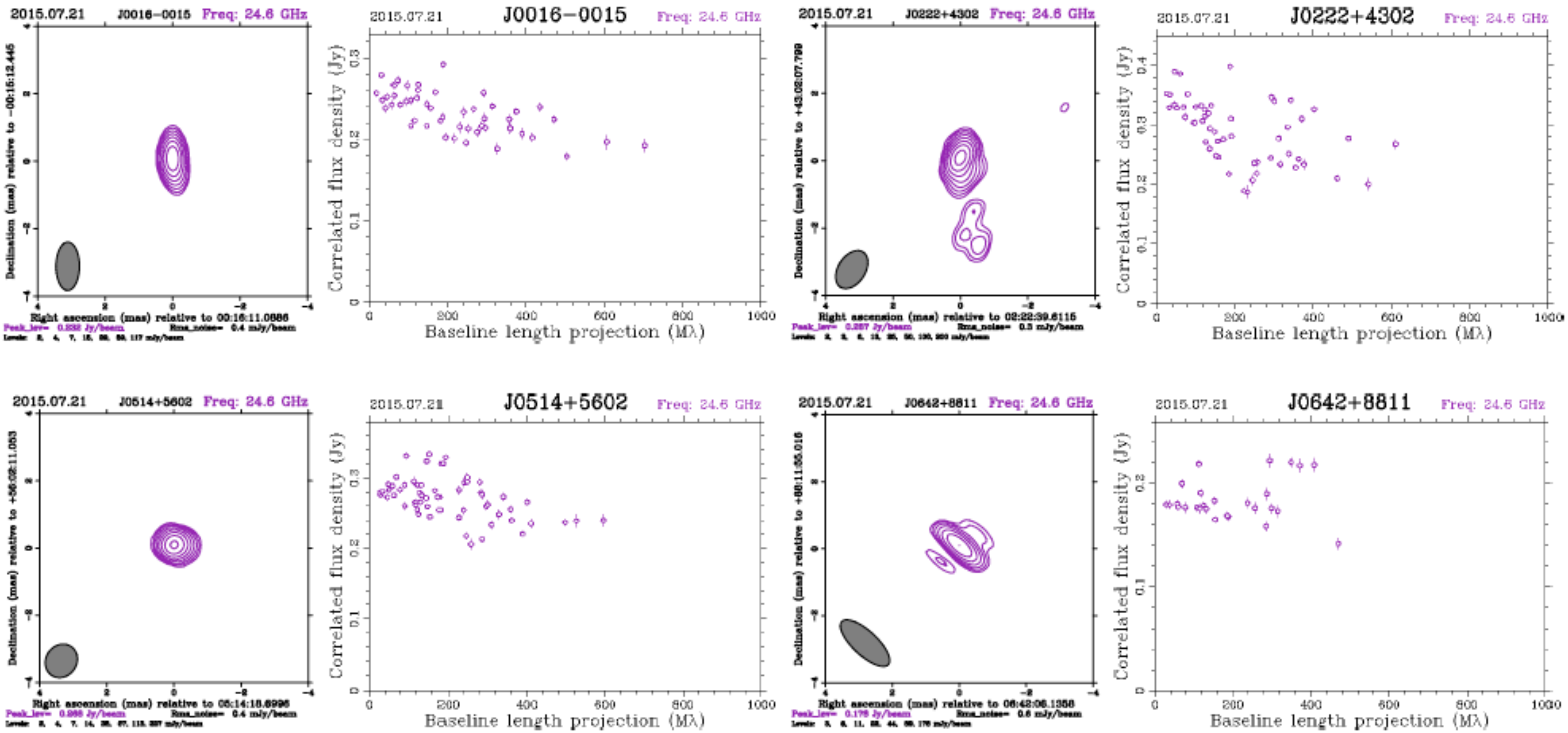
K (24 GHz, 1.2cm): Number sessions 3-10



- Strengths:
  - Uniform spatial density
  - Galactic plane sources (Petrov+ 2006)
  - less structure than S/X (3.6cm)
  - precision < 100 μas
  - needed ~ 0.25 million observations vs. SX's 12 million!

- Weaknesses:
  - Ionosphere only partially calibrated by GPS.
  - No solar plasma calibrations
  - South (δ < -30 deg) weak due to limited HartRAO, South Africa to Hobart, Tasmania data

Imaging: VLBA at 24 GHz (1.2cm) (de Witt et al, 2016)



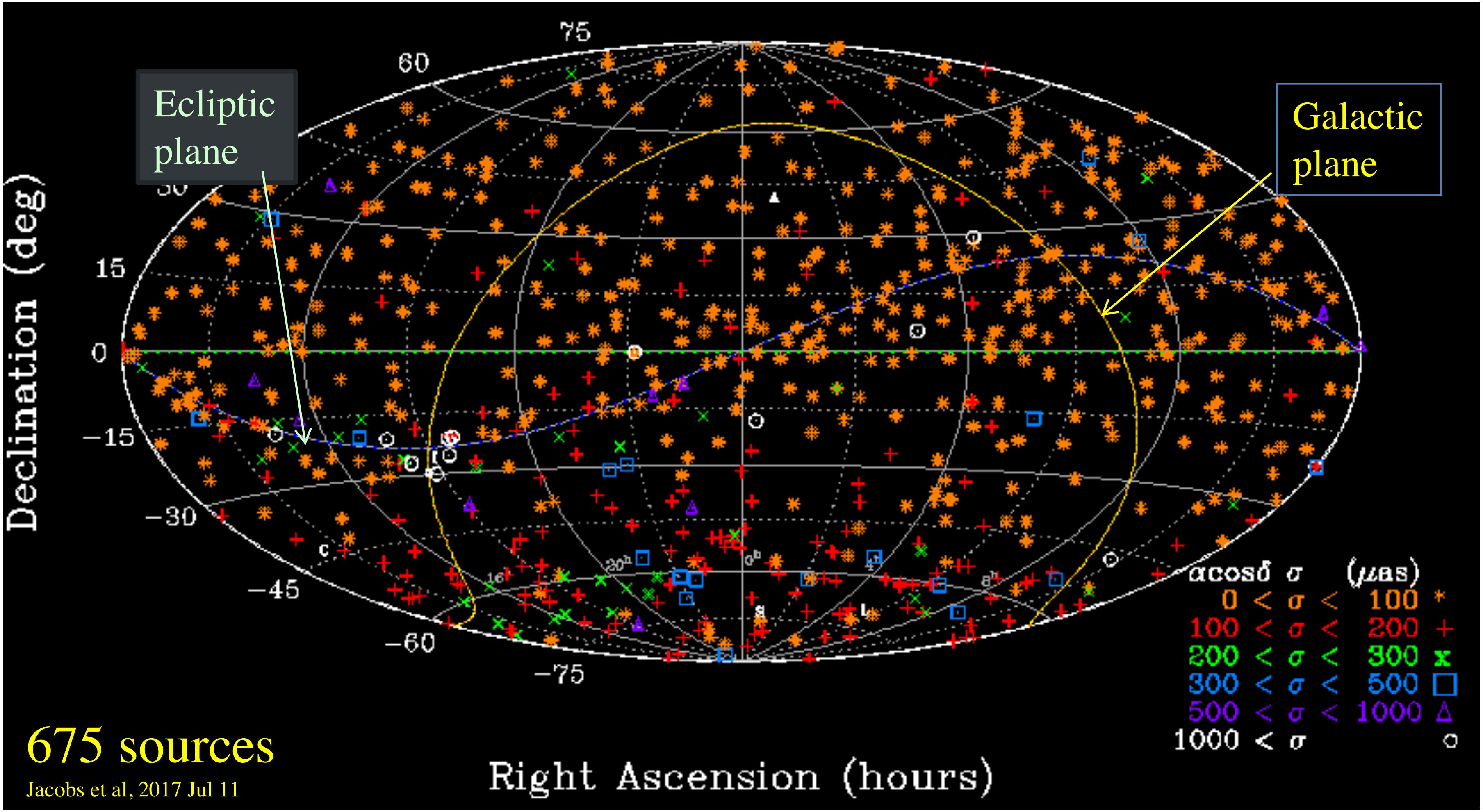
K-band (24 GHz) imaging shows VLBI sources are compact on millarcsec scales.

Data for 500+ sources acquired. Processing limited by available analyst resources.

Imaging will be prioritized as comparison outliers pinpoint sources of interest

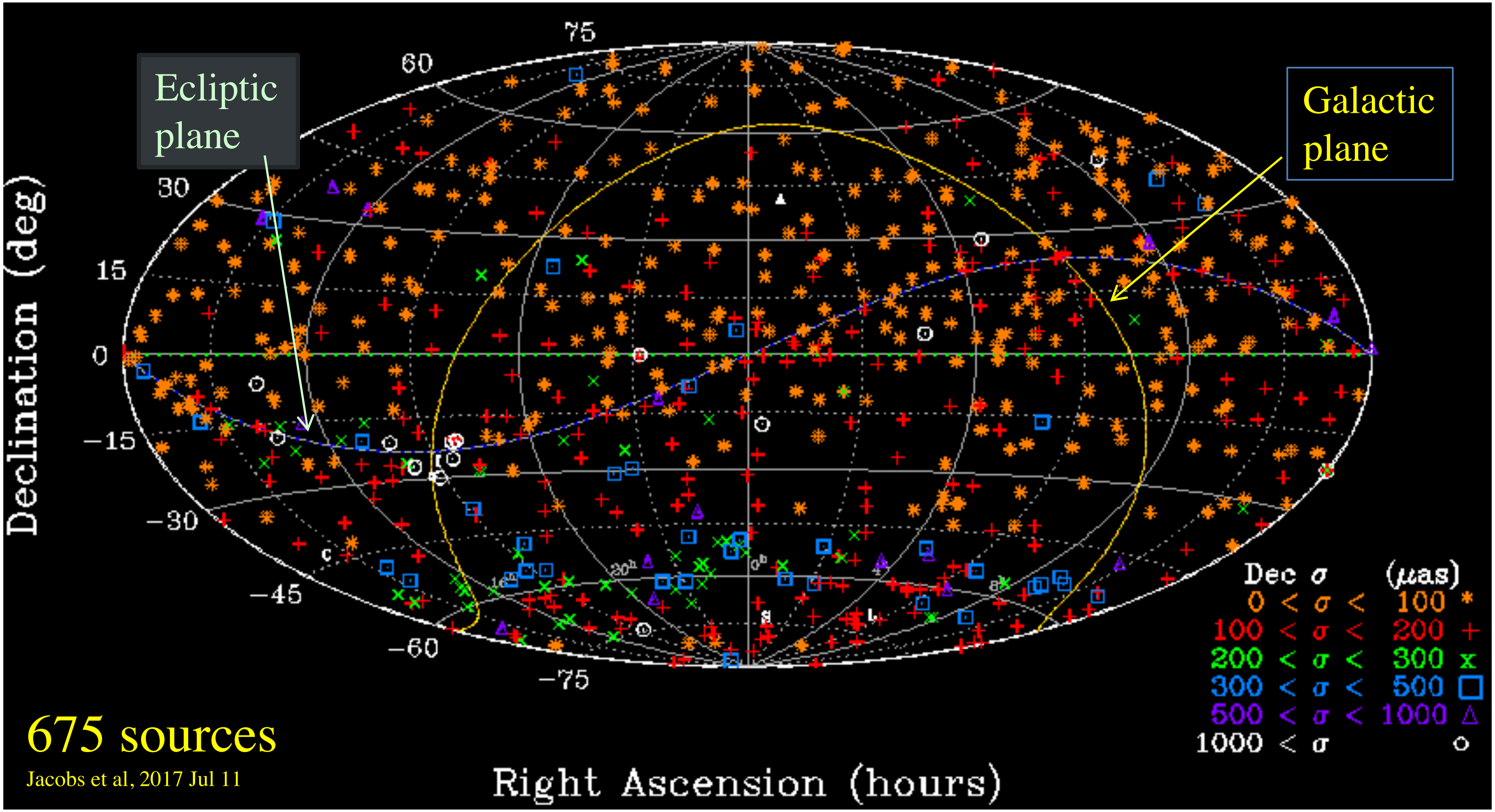
The authors gratefully acknowledge use of the Very Long Baseline Array under the US Naval Observatory's time allocation. This work supports USNO's ongoing research into the celestial reference frame and geodesy.

Ka (32 GHz, 9mm) Combined NASA/ESA Network



- Strengths:
  - Uniform spatial density
  - less structure than S/X (3.6cm)
  - precision < 100 μas
  - needed only 60K observations vs. SX's 12 million!
- Weaknesses:
  - Poor near Galactic center due to inter-stellar media scattering
  - South weak due to limited time on ESA's Argentina station
  - Limited Argentina-California data makes vulnerable to δ zonals
  - Limited Argentina-Australia weakens δ from -45 to -60 deg

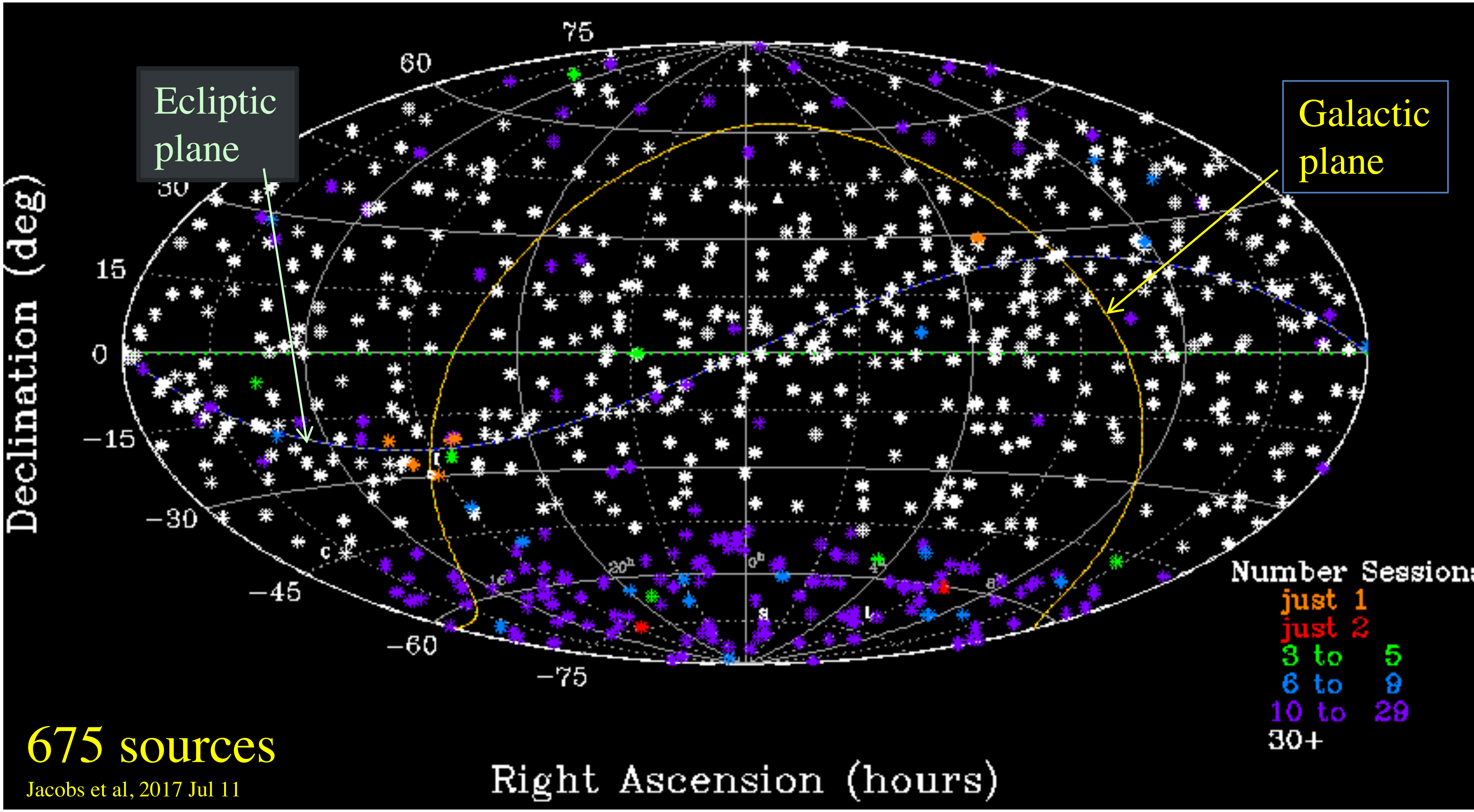
X/Ka (32 GHz): Dec precision weaker, esp. δ -45 to -60



- Strengths:
  - Uniform spatial density
  - less structure than S/X (3.6cm)
  - precision < 100 μas
  - needed only 60K observations vs. SX's 12 million!

- Weaknesses:
  - Poor near Galactic center due to inter-stellar media scattering
  - South weak due to limited time on ESA's Argentina station
  - Limited Argentina-California data makes vulnerable to δ zonals
  - Limited Argentina-Australia weakens δ from -45 to -60 deg

X/Ka (32 GHz): Number sessions better than SX or K



- Strengths:
  - Uniform spatial density
  - less structure than S/X (3.6cm)
  - precision < 100 μas
  - needed only 60K observations vs. SX's 12 million!

- Weaknesses:
  - Poor near Galactic center due to inter-stellar media scattering
  - South weak due to limited time on ESA's Argentina station
  - Limited Argentina-California data makes vulnerable to δ zonals
  - Limited Argentina-Australia weakens δ from -45 to -60 deg

Ka-band combined NASA/ESA Deep Space Net

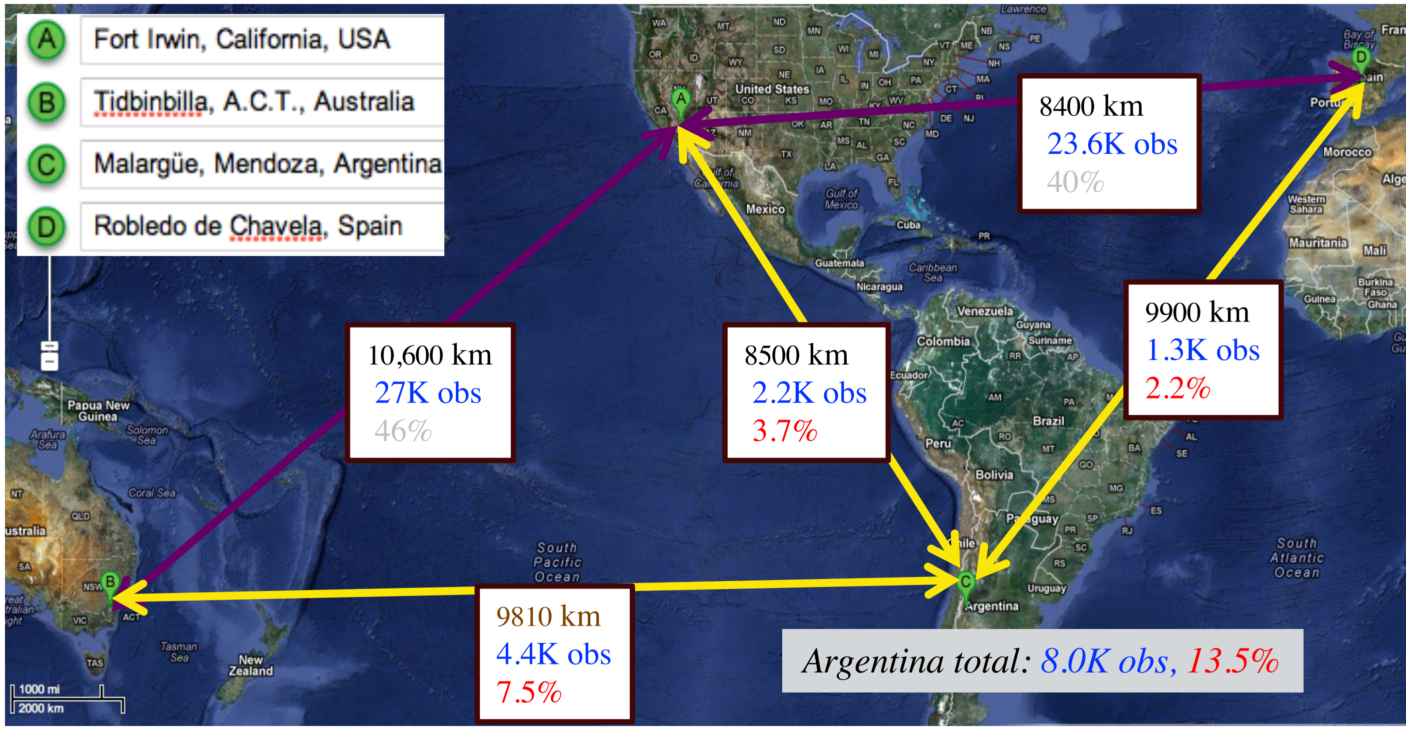
ESA Argentina to NASA-California under-observed by order of magnitude!

<u>Baseline percentages</u>

- Argentina is part of 3/5 baselines or 60% but only 13% of obs
- Aust- Argentina 7.5%
- Spain-Argentina 2.2%
- Calif- Argentina 3.7%

This baseline is under-observed by a factor of ~ 12.

More time on ESA's Argentina station would have a huge, immediate impact!!



Maps credit: Google maps

ESA's Argentina 35-meter antenna **adds 3 baselines** to DSN's 2 baselines

- Full sky coverage by accessing south polar cap
- near perpendicular mid-latitude baselines: CA to Aust./Argentina

Three VLBI bands compare to better than 200 μas RMS
Gaia DR-1 precision ~ 500 μas. DR-2 vs. VLBI may reveal zonals

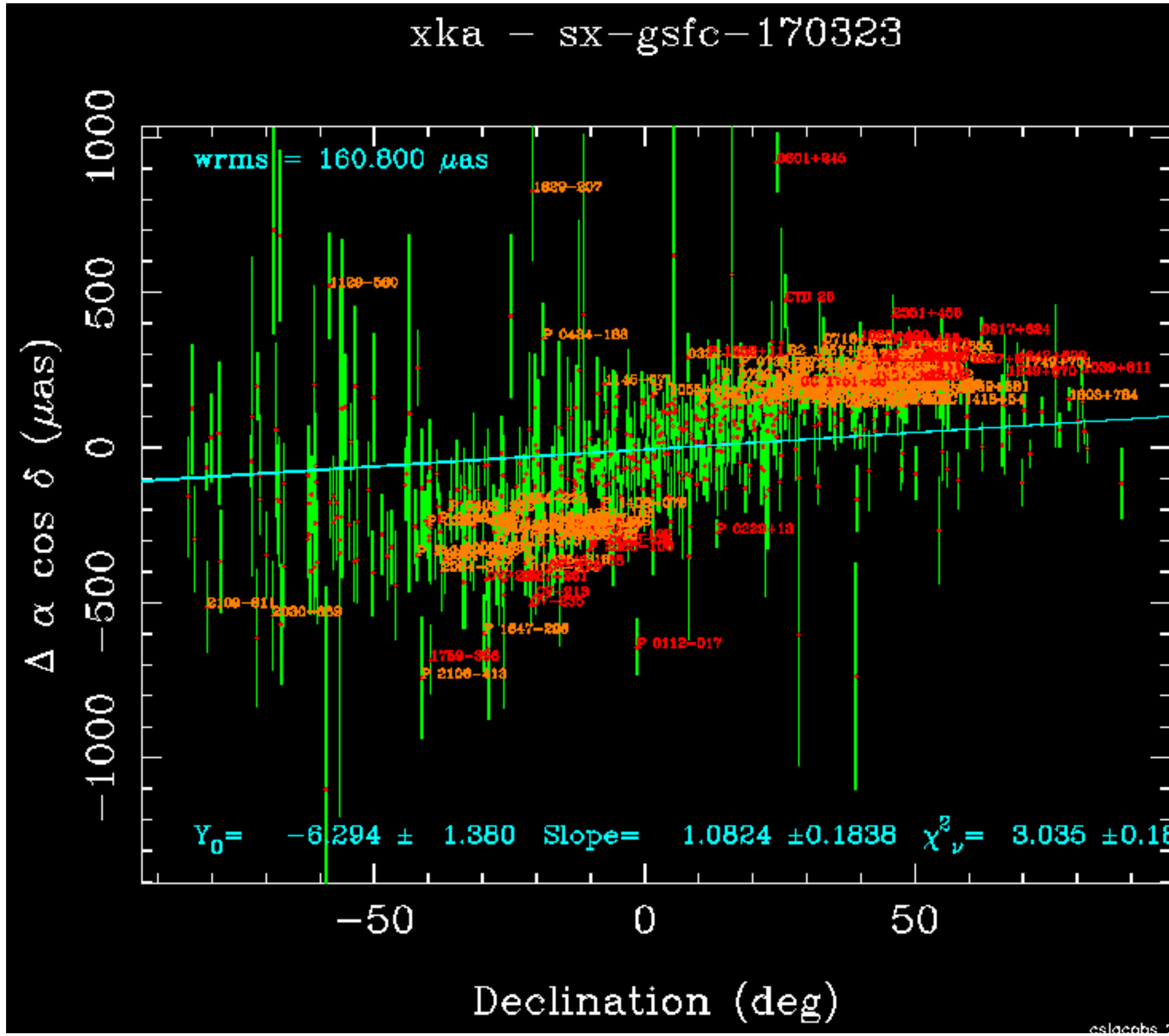
Zonal Errors

- ΔRA vs. Dec:
  ~300 μas in south, 200 μas in north
- Need 2 baselines to get 2 angles:
  California-Canberra: 24K obs
  California-Argentina: 2K obs

-> Need more California-Argentina data to overcome this 12 to 1 distortion in sampling geometry. ESA's Malargüe is key.

- Usuda, Japan 54-m XKa (2019) would improve North-South sampling geometry and thus control declination zonal differences.

XKa vs. SX: Zonal errors

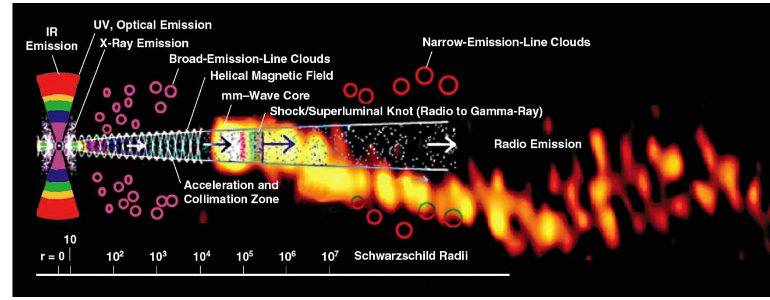


Credit: SX astrometry, D. Gordon

The goal:

Alignment of Optical and Radio into Common Frame

Optical-Radio Frame Tie Geometry

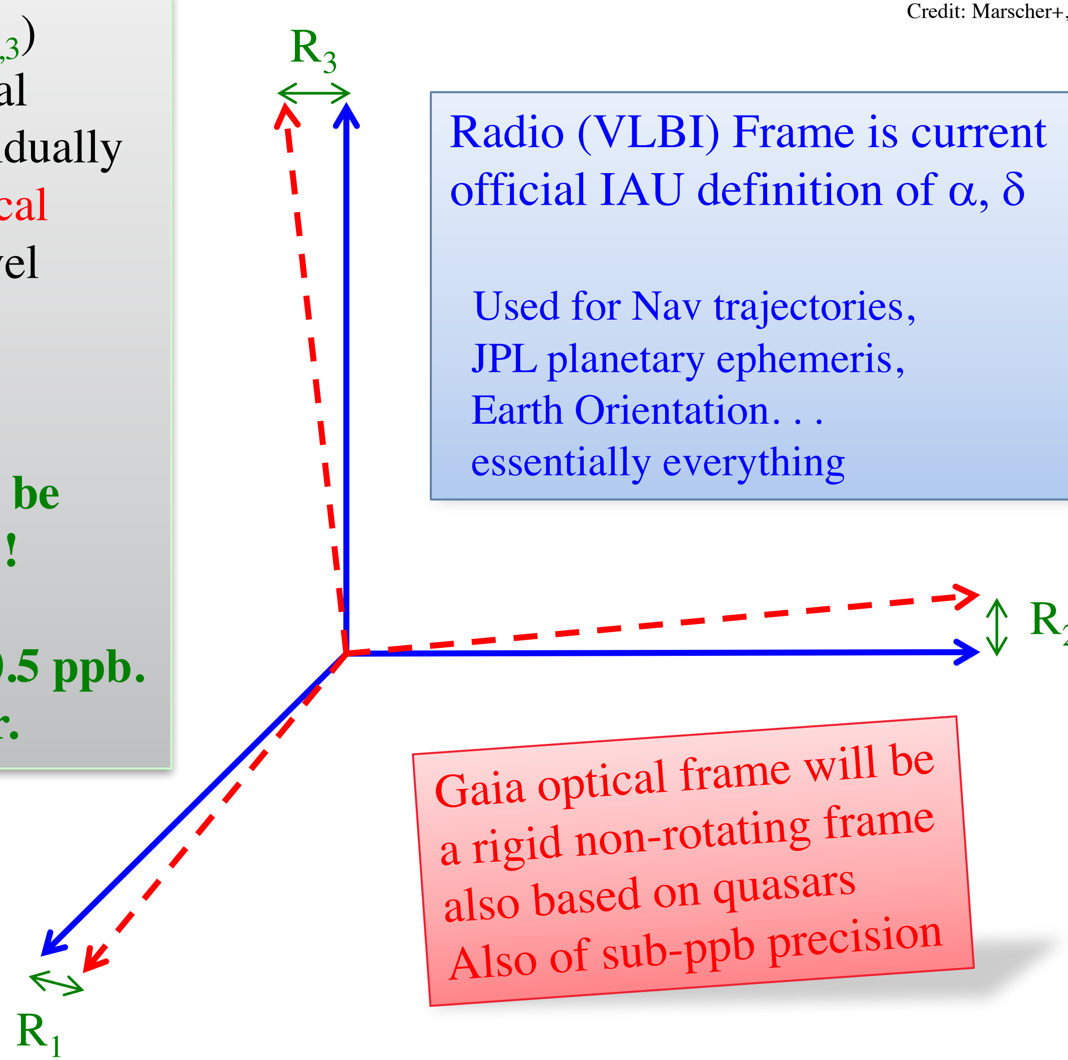


Credit: Marscher+, Krichbuam+

Determine 3 small rotations ($R_{1,2,3}$) and zonal differences i.e. spherical harmonics Y_{lm} between the individually rigid, non-rotating radio and optical frames to sub-part per billion level

Allows seamless integration into united frame.
More than 1 billion objects will be integrated into common frame!!

Object precision to < 100 μas, 0.5 ppb. want tie errors 10 times smaller.



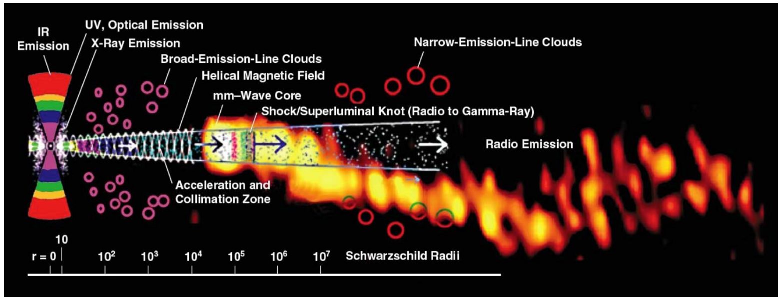
Radio (VLBI) Frame is current official IAU definition of α, δ

Used for Nav trajectories,
JPL planetary ephemeris,
Earth Orientation. . .
essentially everything

Gaia optical frame will be a rigid non-rotating frame also based on quasars
Also of sub-ppb precision

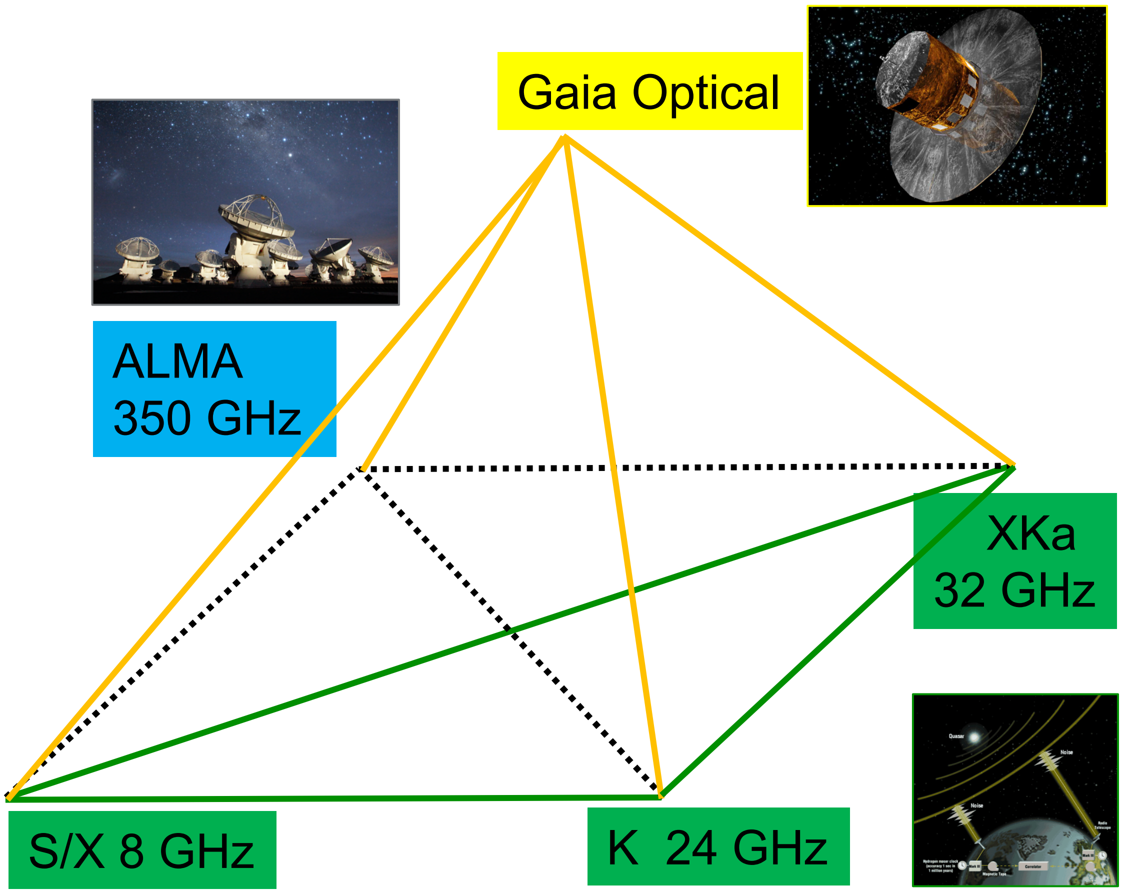
Frame Tie Comparisons

Tying Optical and Radio Celestial Frames



Credit: Marscher+, Krichbaum+

Systematics to be flushed out via Inter-comparison of multiple high precision frames.



<u>Systematics:</u>

Gaia: 60 mas beam sees
Host galaxy, foreground stars, etc.

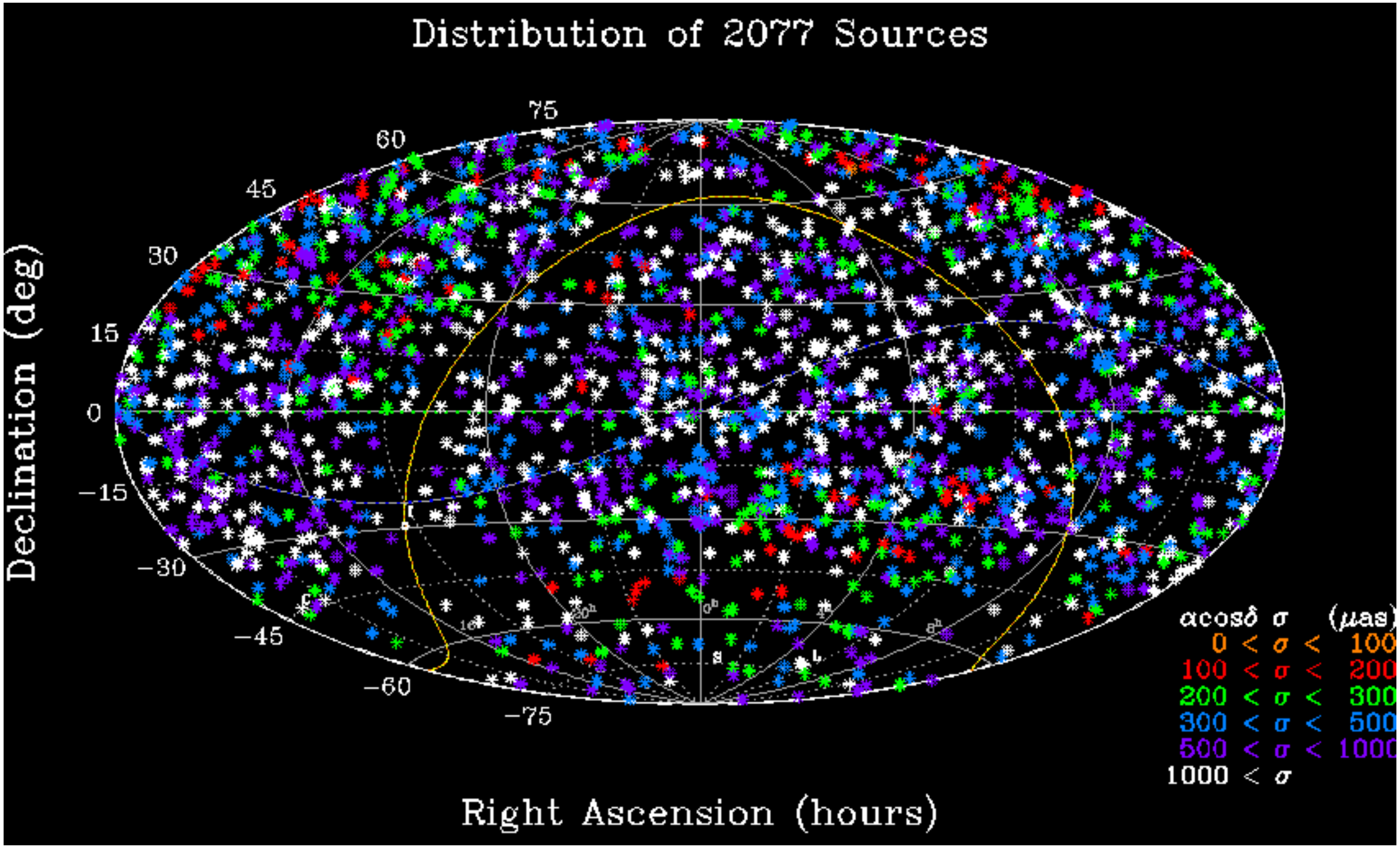
ALMA: pilot obs bright end ~5^{mag}
Waiting on 10km+ configurations

VLBI: All bands need more
southern data

S/X: Source structure
K: Ionosphere
XKa: Argentina baselines
under-observed

Tying optical and Radio Celestial Frames

Gaia DR1-aux vs. SX VLBI



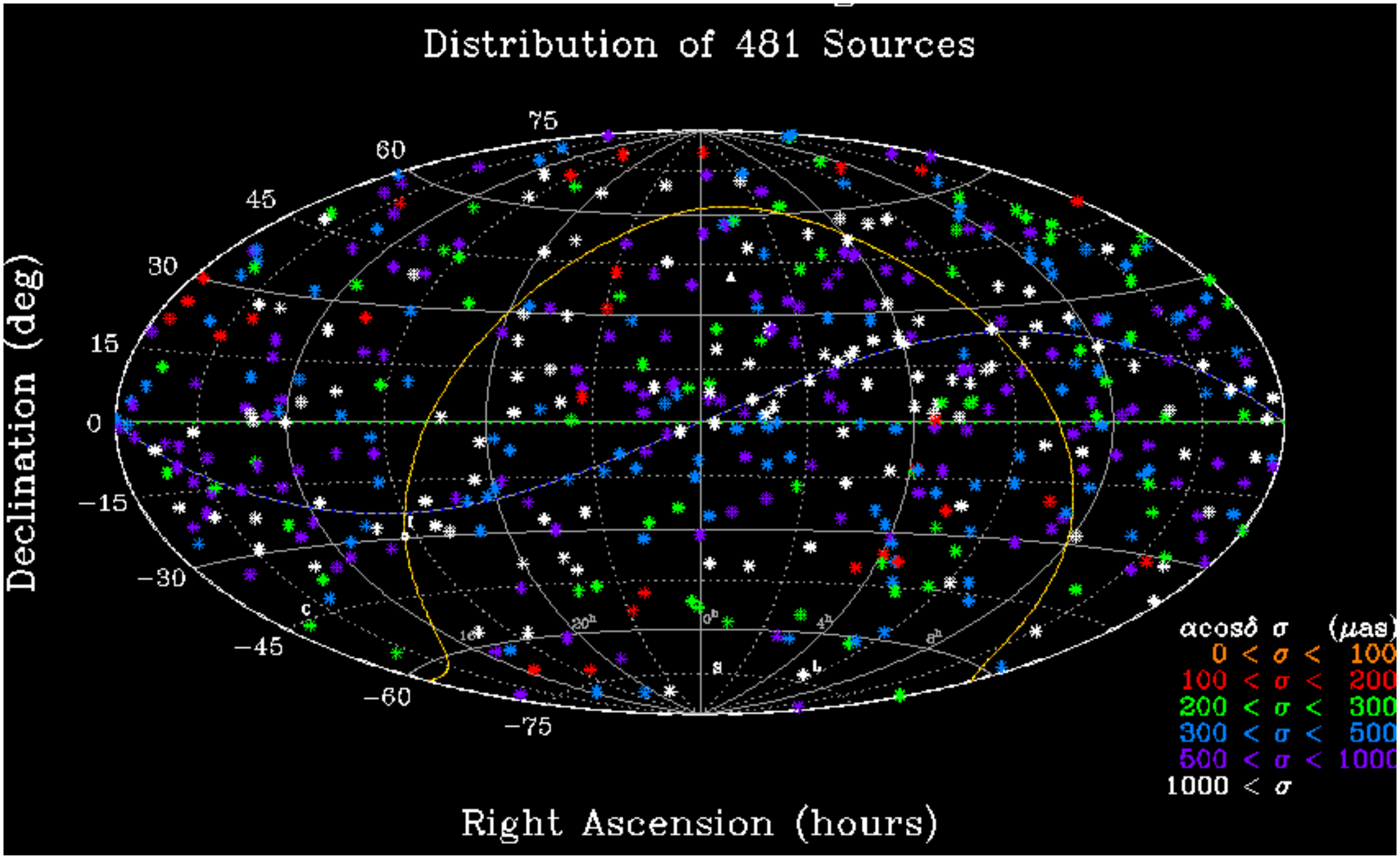
~5 times more sources than K or Ka

Fairly uniform distribution. A bit weaker in the south

Color code shows Gaia formal sigmas.

Tying optical and Radio Celestial Frames

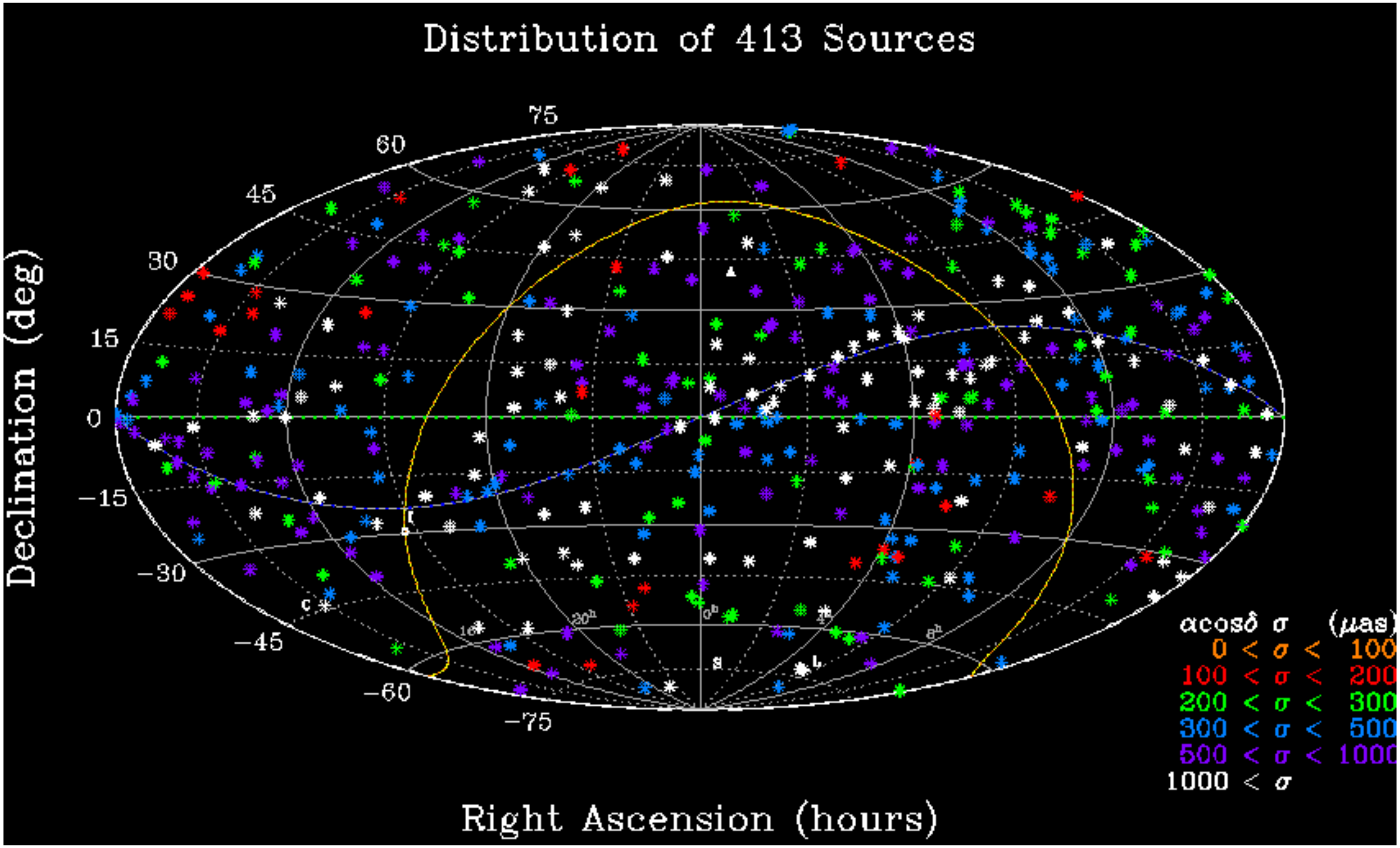
Gaia DR1-aux vs. K VLBI



Fairly uniform distribution.
Color code shows Gaia formal sigmas.

Tying optical and Radio Celestial Frames

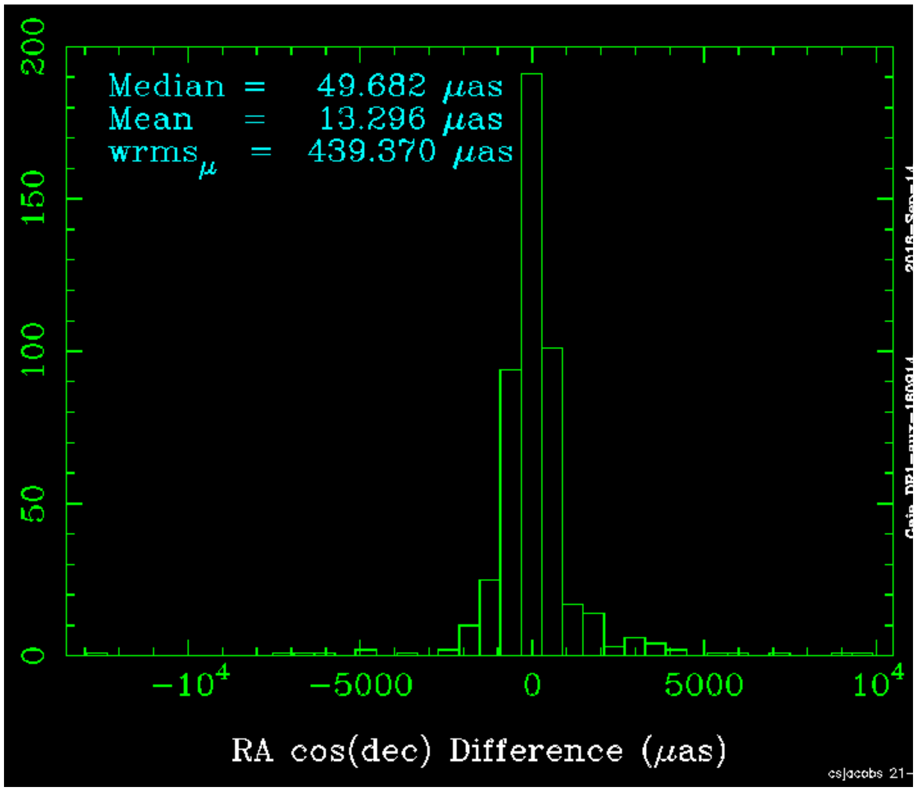
Gaia DR1-aux vs. Ka VLBI

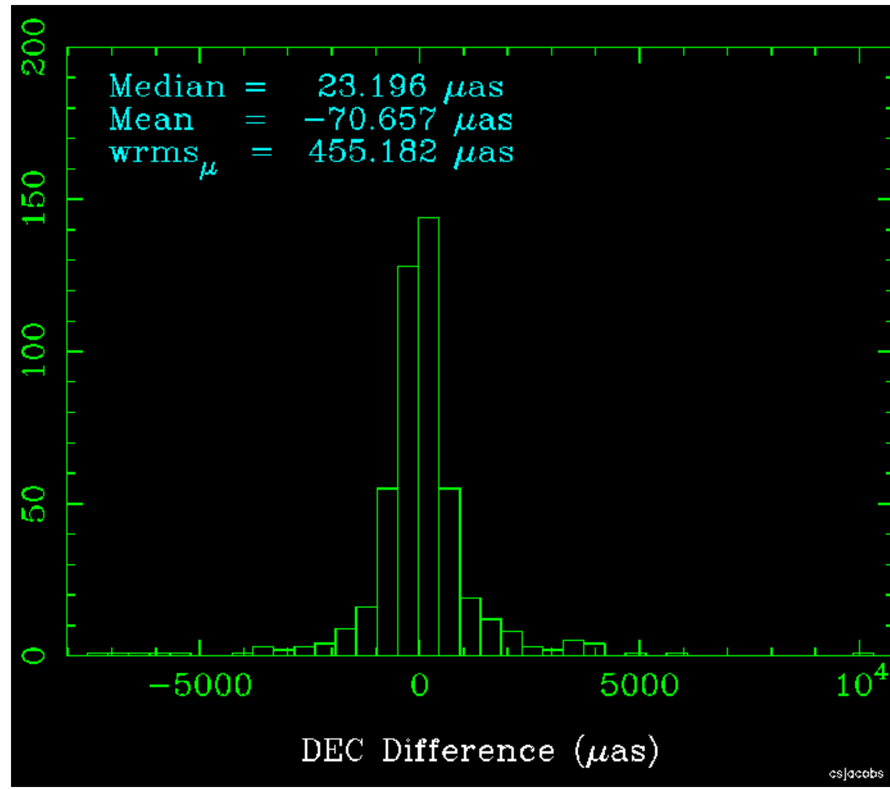


Fairly uniform distribution.
Color code shows Gaia formal sigmas.

Tying optical and Radio Celestial Frames

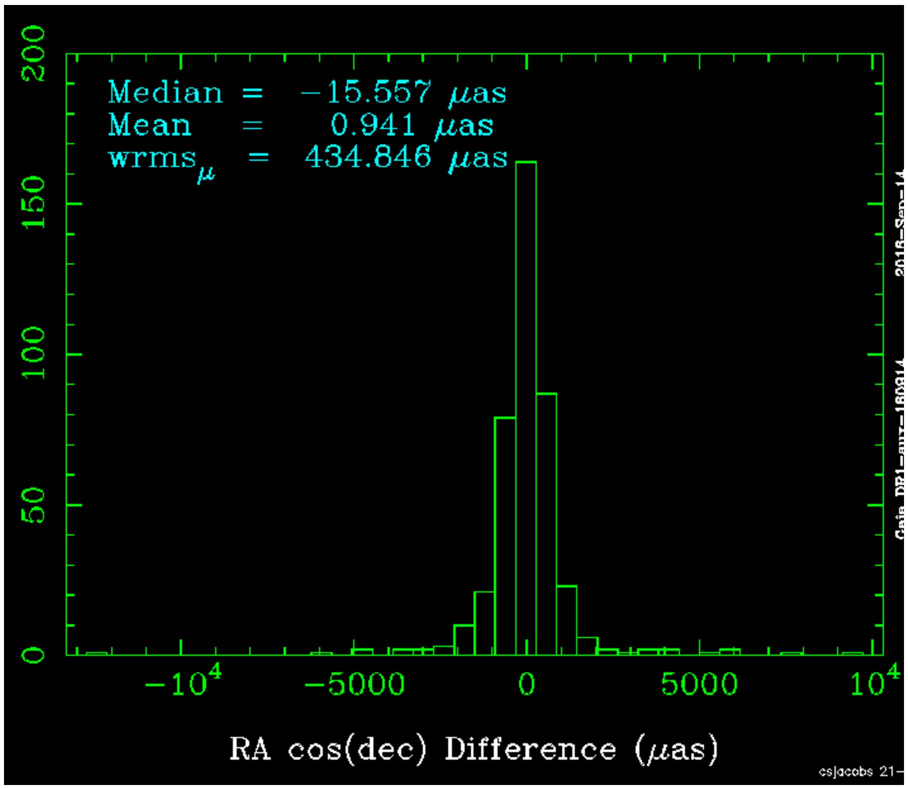
Gaia DR1-aux vs. K VLBI

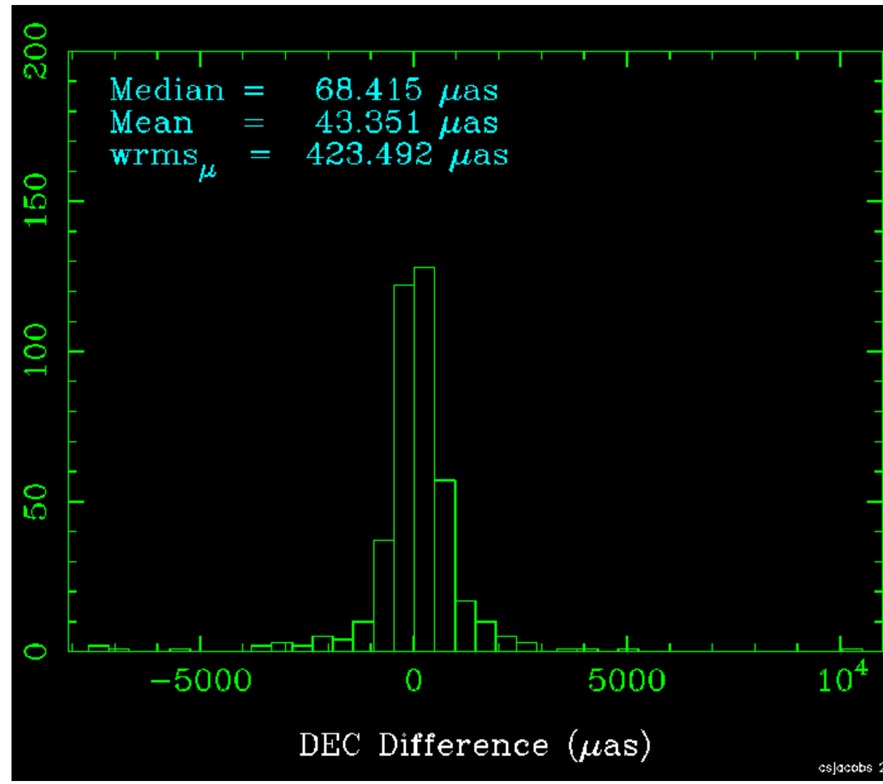




wRMS Ra and Dec differences about 440 μas (2 nrad)
Normalized differences are about 1.1 indicating realistic errors

Gaia DR1-aux vs. Ka VLBI

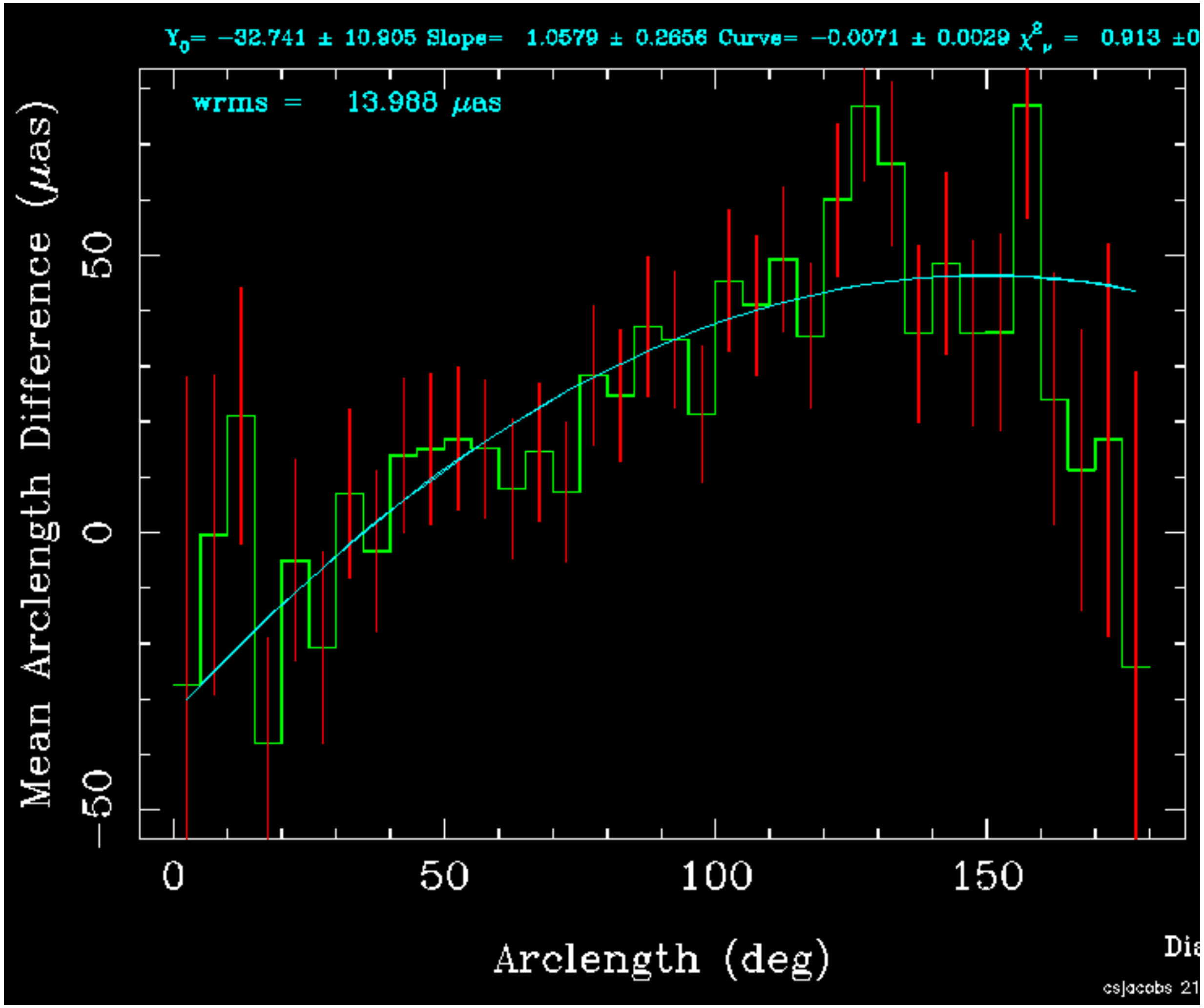




wRMS Ra and Dec differences about 400 μas (2 nrad)
Normalized differences are about 1.1 indicating realostic errors

Tying optical and Radio Celestial Frames

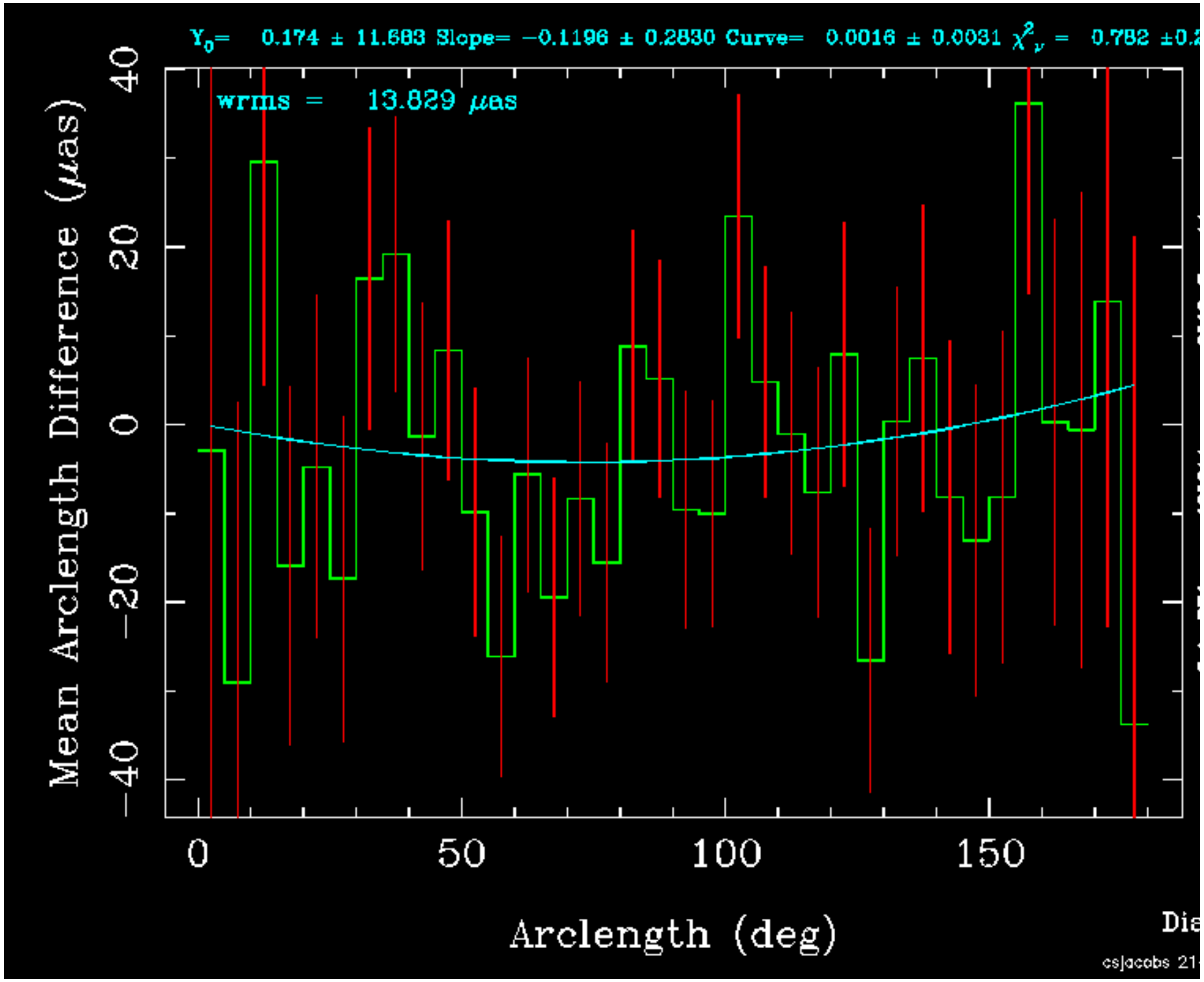
Gaia DR1-aux vs. K VLBI



Arc differences vs. arclength bins show distortion at 50 μas level

Tying optical and Radio Celestial Frames

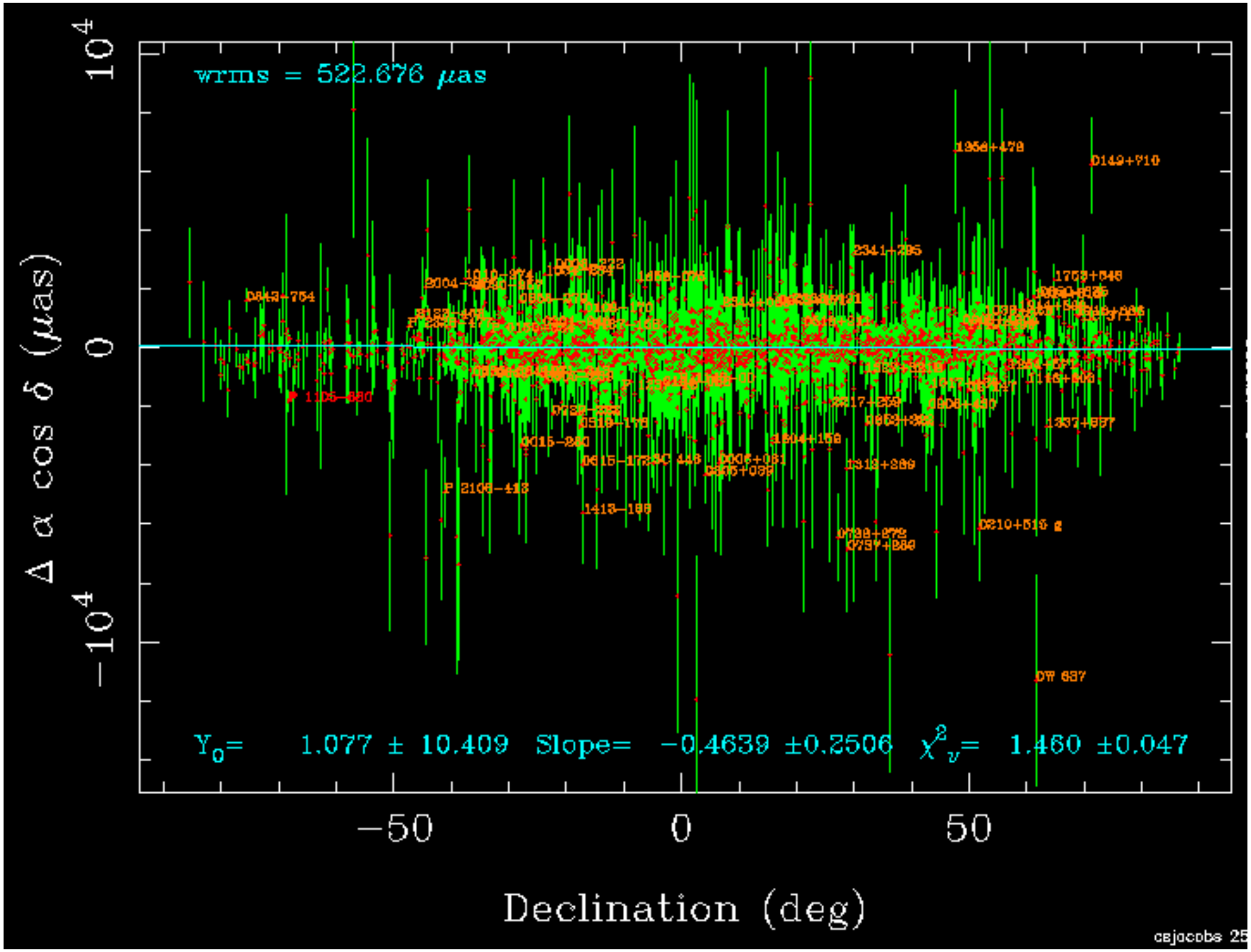
Gaia DR1-aux vs. Ka VLBI



Arc differences steady vs. arclength bins at 15 μas level

Tying optical and Radio Celestial Frames

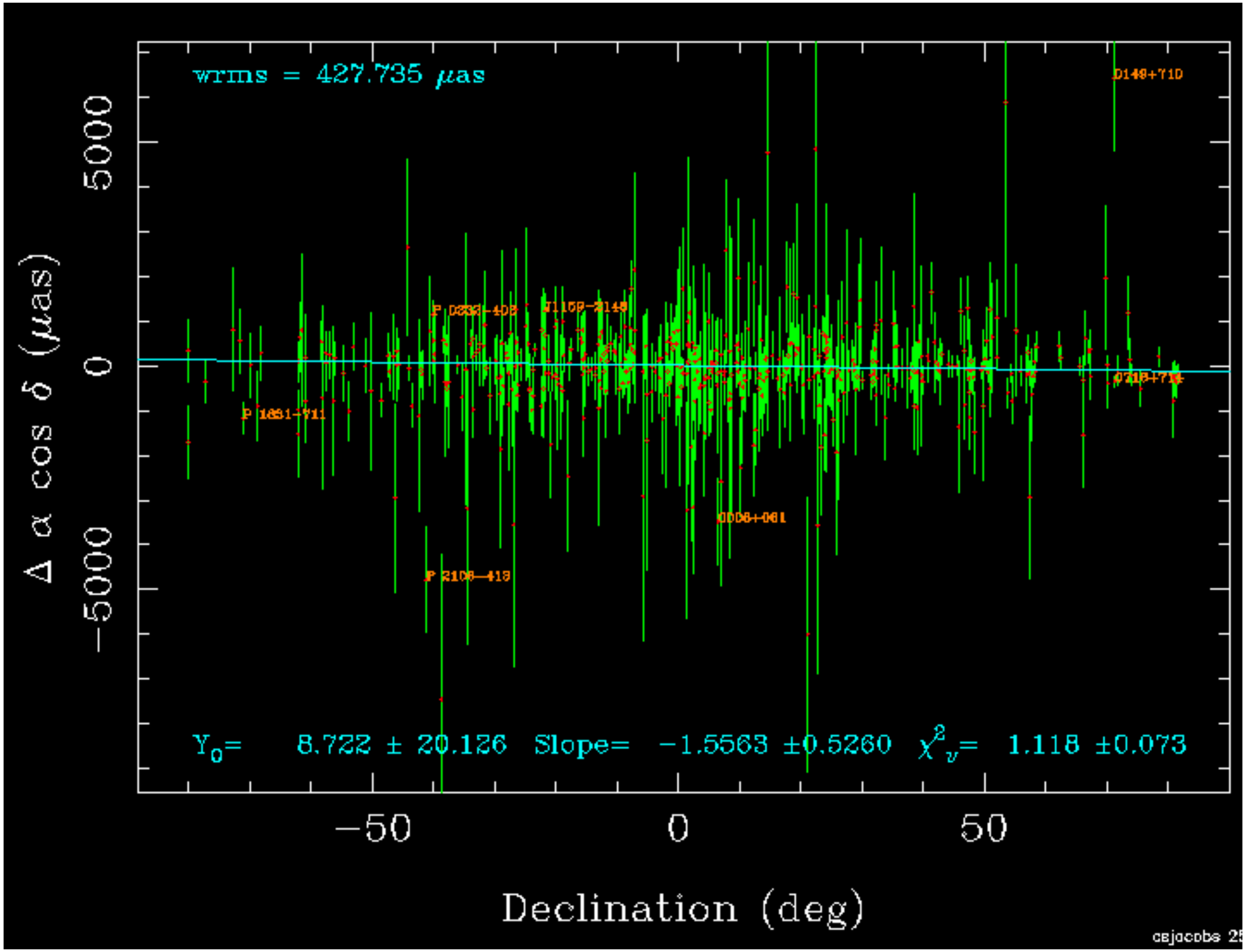
Gaia DR1-aux vs. SX VLBI



Systematic tilt: $\Delta\alpha$ vs. δ has 2 sigma slope of -0.46 +- 0.25 μas/deg

Tying optical and Radio Celestial Frames

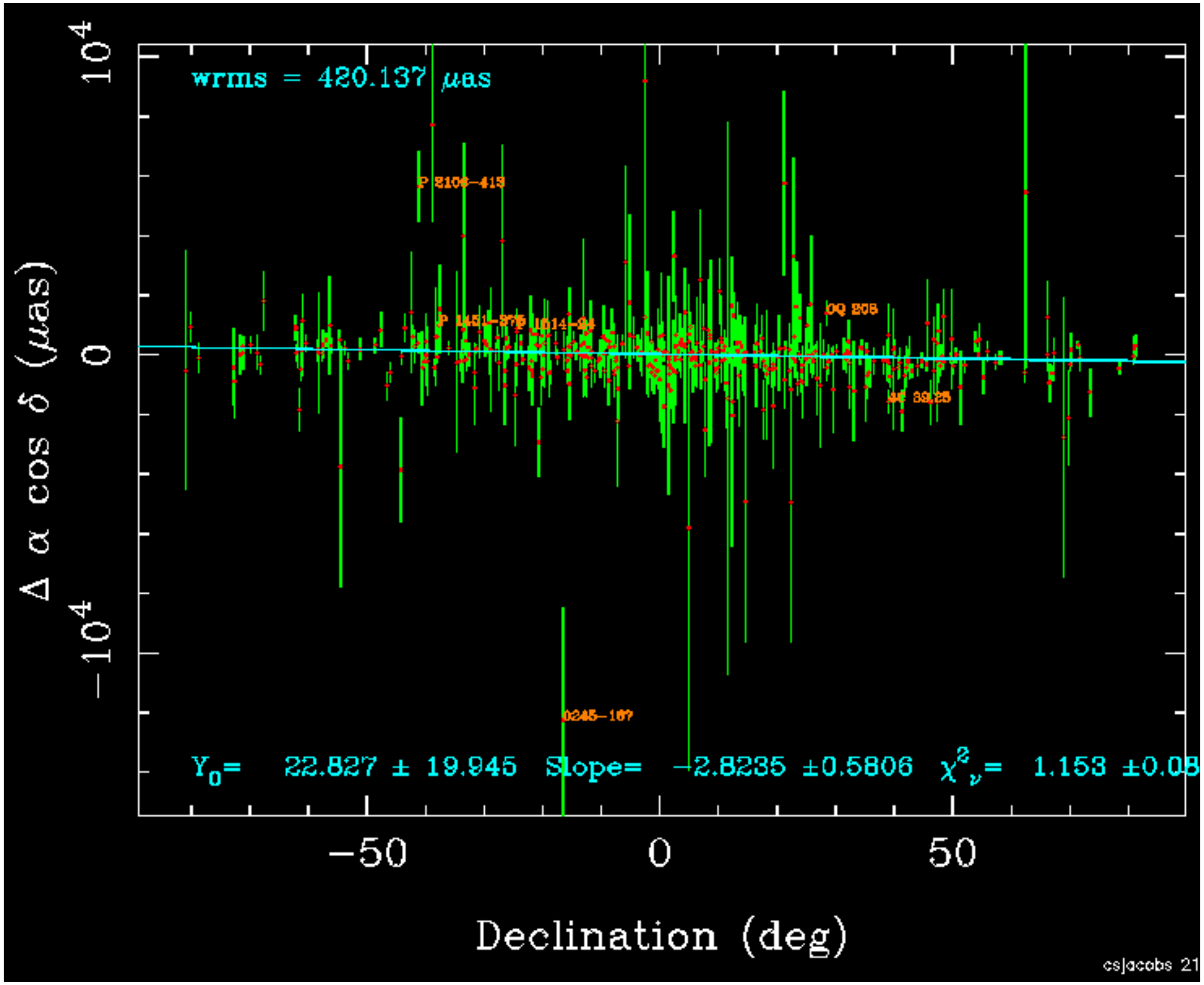
Gaia DR1-aux vs. K VLBI



Systematic tilt: $\Delta\alpha$ vs. δ has 3 sigma slope of -1.56 +- 0.53 μas/deg

Tying optical and Radio Celestial Frames

Gaia DR1-aux vs. Ka VLBI



Systematic tilt: Δα vs. δ has 4.9 sigma slope of -2.8 +- 0.6 μas/deg

Tying optical and Radio Celestial Frames

Gaia DR1-aux vs. VLBI

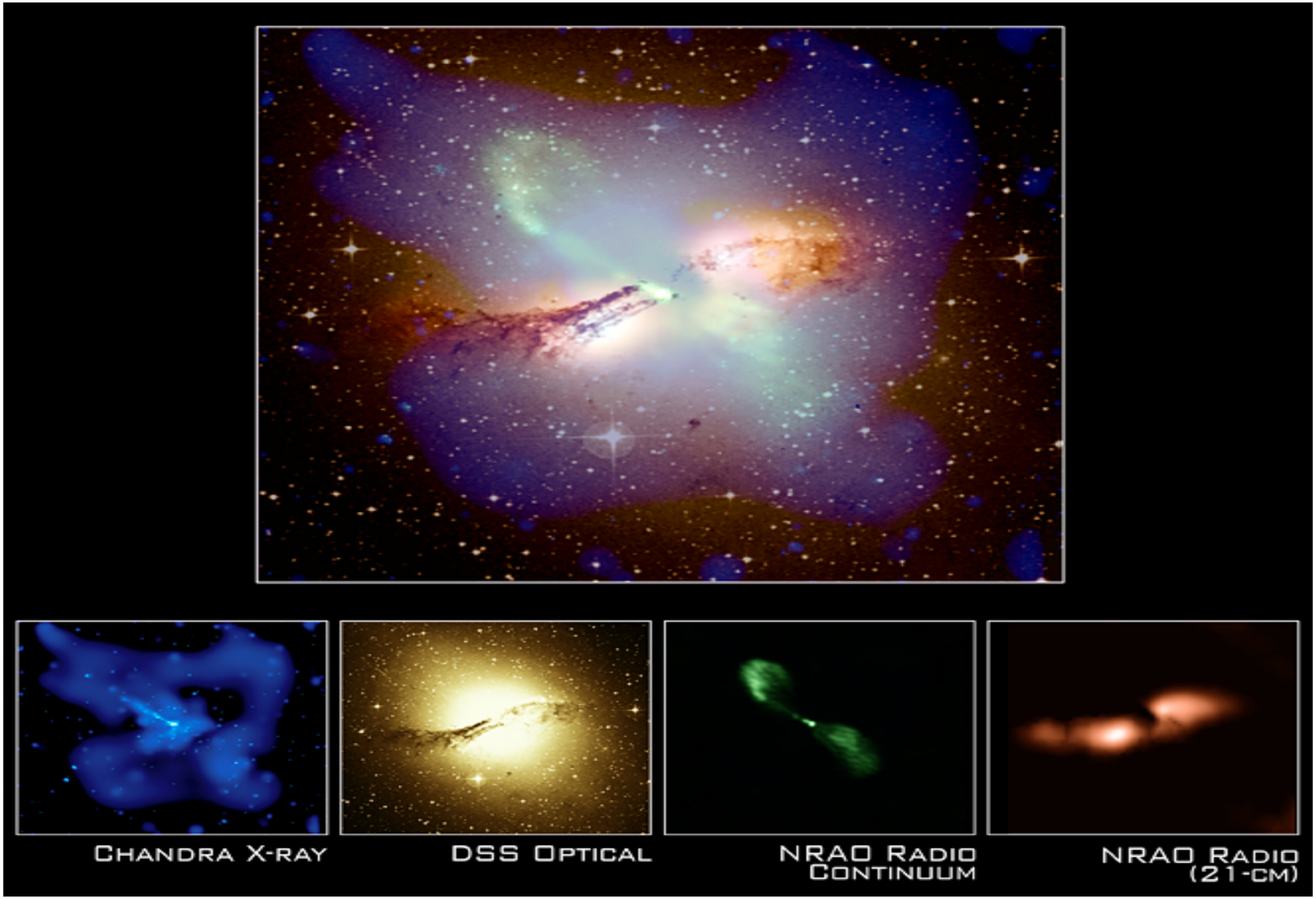
	SX-band 8 GHz 3.6cm	K-band 24 GHz 1.2 cm	XKa-band 32 GHz 0.9 cm
# Observations	12 million	0.25 million	0.06 million
# sources	1926	473	405
# outliers > 5σ	100	13	6
% outliers	5.2 %	2.7 %	1.5 %
α wRMS	523 μas	431 μas	433 μas
δ wRMS	531 μas	453 μas	418 μas
R_x	-37 +- 13	-89 +- 24	57 +- 24
R_y	0 +- 11	14 +- 21	32 +- 21
R_z	-29 +- 13	-13 +- 23	21 +- 24
Δα vs. δ tilt (μas/deg)	-0.46 +- 0.25	-1.55 +- 0.53	-2.83 +- 0.58

Rx vulnerable
To trop errors

Hints that results improve by going to higher radio frequency
However, the above results do not use exact same objects

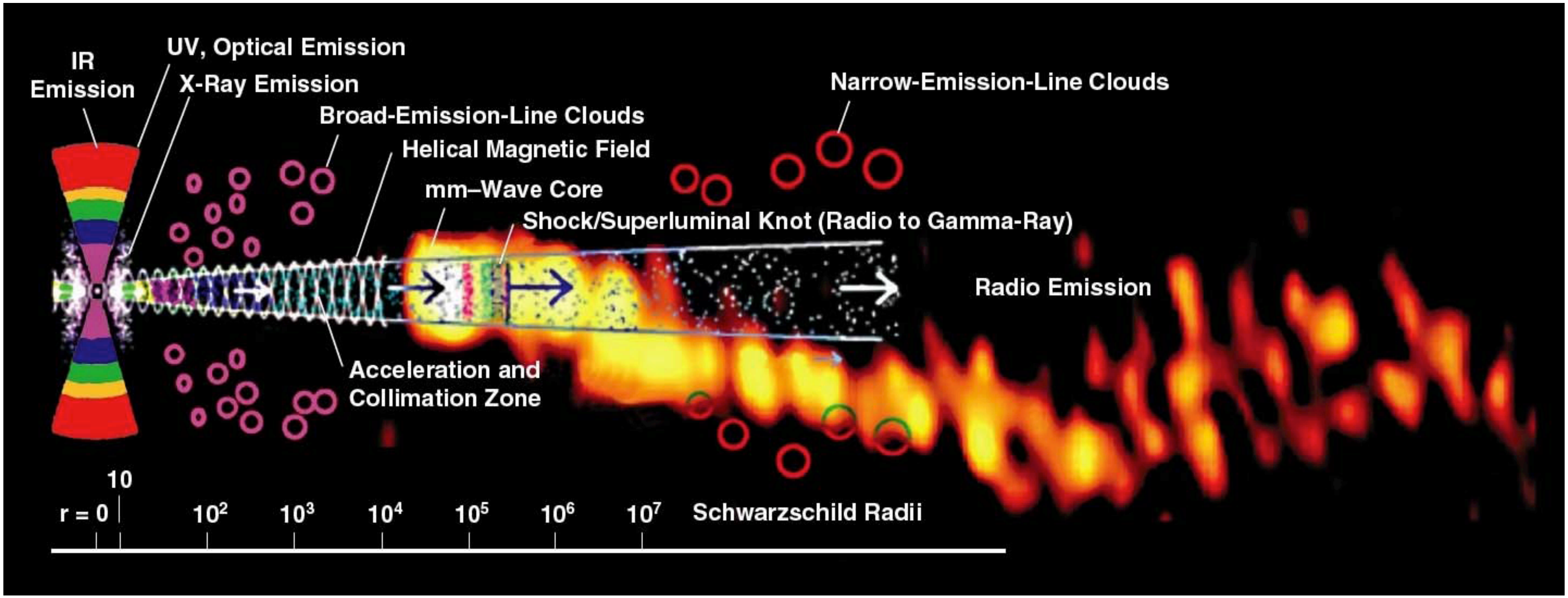
A last look at Optical vs. Radio Astrometric offsets

Example Extragalactic Source: Centaurus-A in X-ray, Optical, Radio



Credits: X-ray (NASA/CXC/M. Karovska et al.); Radio 21-cm image (NRAO/VLA/Schiminovich, et al.), Radio continuum image (NRAO/VLA/J.Condon et al.); Optical (Digitized Sky Survey U.K. Schmidt Image/STScI)

Active Galactic Nuclei (*Marscher*)



R~0.1-1 μas 1mas

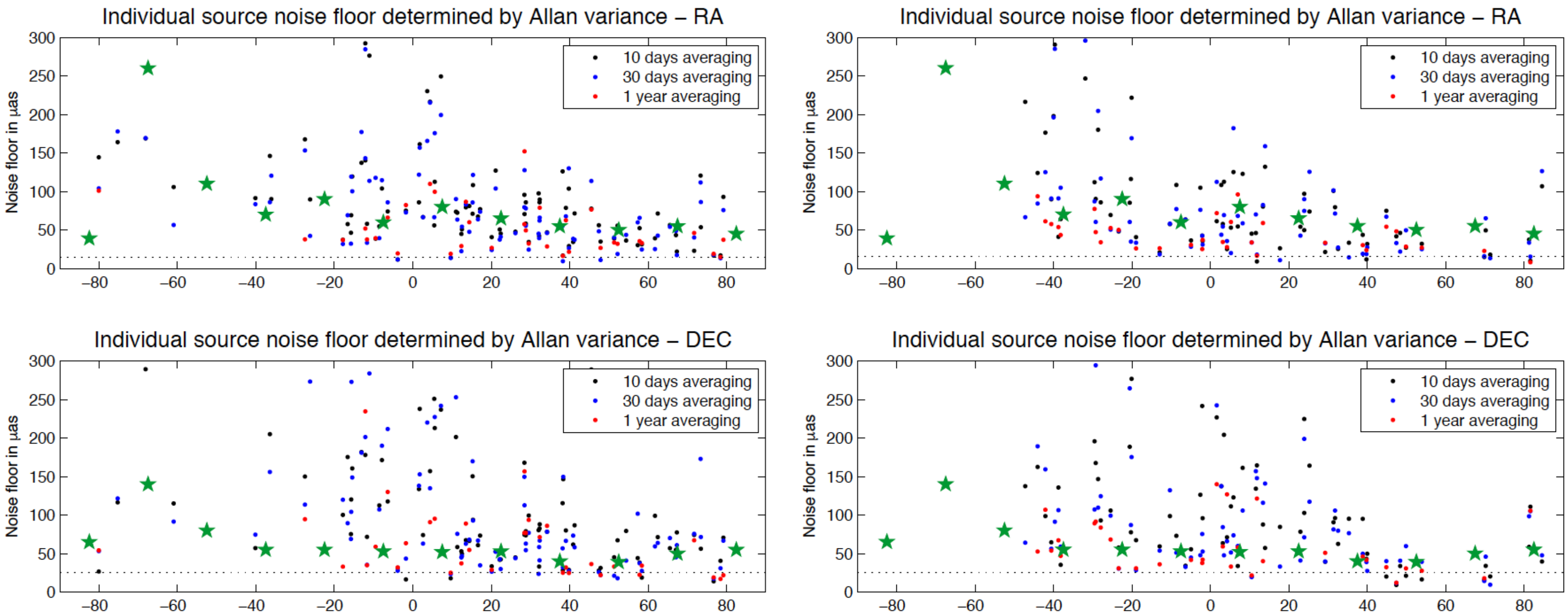
Features of AGN: *Note the Logarithmic length scale.*
"Shock waves are frequency stratified, with highest synchrotron frequencies emitted only close to the shock front where electrons are energized. The part of the jet interior to the mm-wave core is opaque at cm wavelengths. At this point, it is not clear whether substantial emission occurs between the base of the jet and the mm-wave core."

Credits: Alan Marscher, `Relativistic Jets in Active Galactic Nuclei and their relationship to the Central Engine,' Proc. of Science,VI Microquasar Workshop: Microquasars & Beyond, Societa del Casino, Como, Italy, 18-22 Sep 2006. Overlay (not to scale): 3 mm radio image of the blazar 3C454.3 (Krichbaum et al. 1999)

SX VLBI systematic Floor ~ 20 to 30 μas?

Set of Flicker Noise sources

Set of White Noise sources



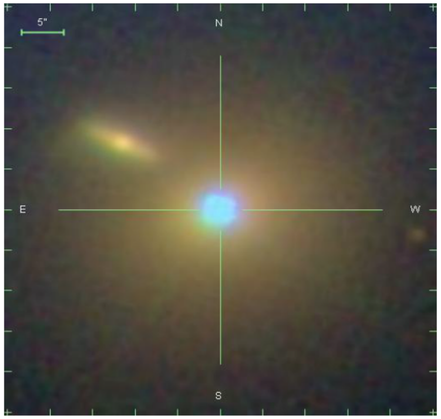
Green ★ : ICRF2 noise floor - average on sources in 15° declination bands.

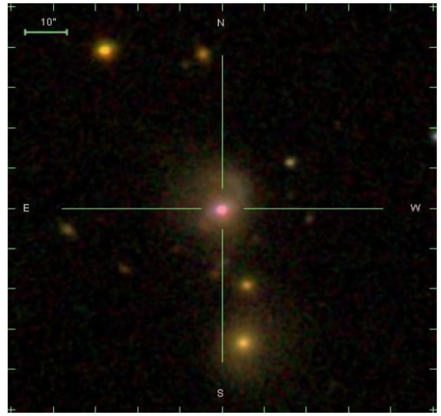
Attention! This method uses ALL "good" sessions, contrary to the decimation test.

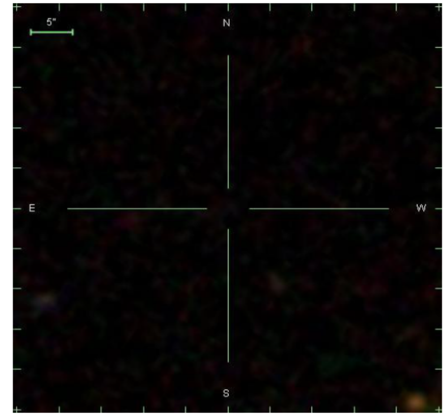
Le Bail+ (EVGA, 2017) use Allan variance test on position time histories
to determine when averaging no longer helps—systematic floor is encountered.
Structure part of this floor should be several times smaller at K (24 GHz) and Ka (32 GHz)

Optical vs. Radio systematics offsets

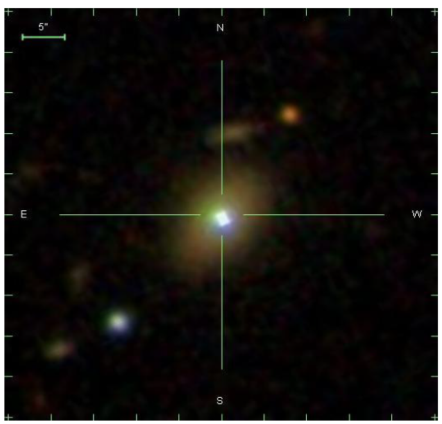
SDSS Optical images of quasars (scale 5-10 asec)

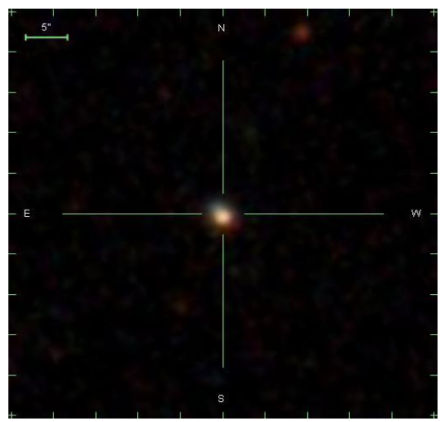


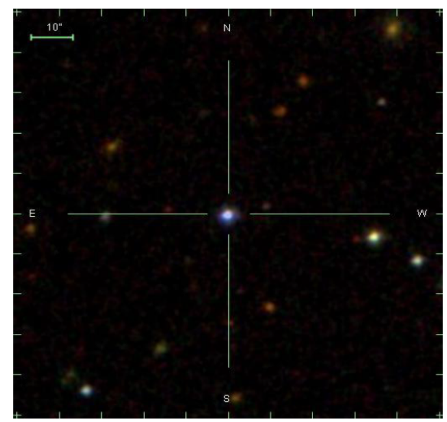




1101+384 0007+106 0920+390





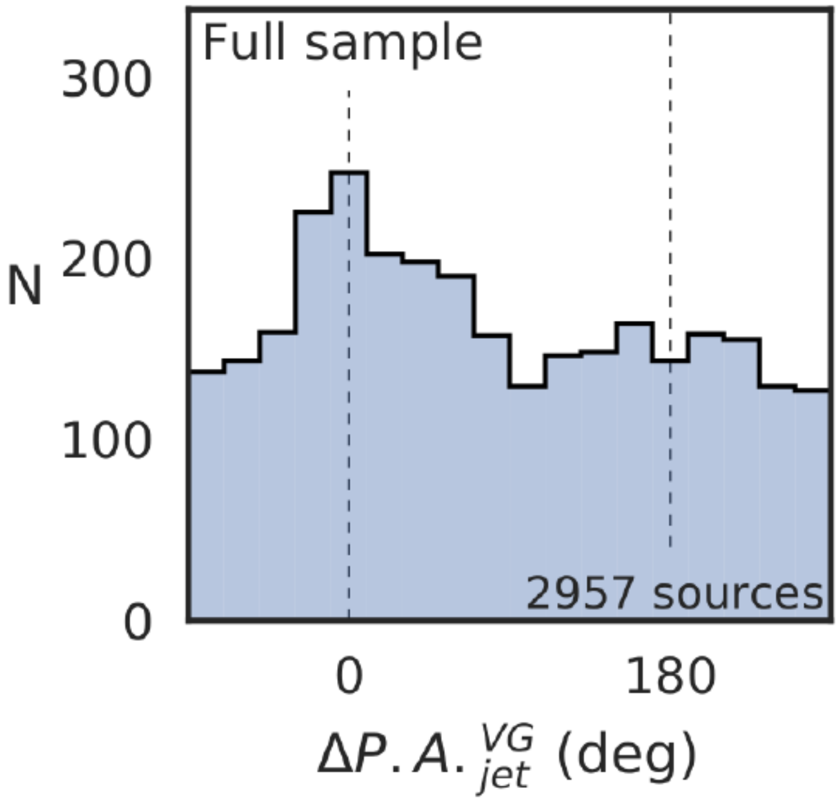


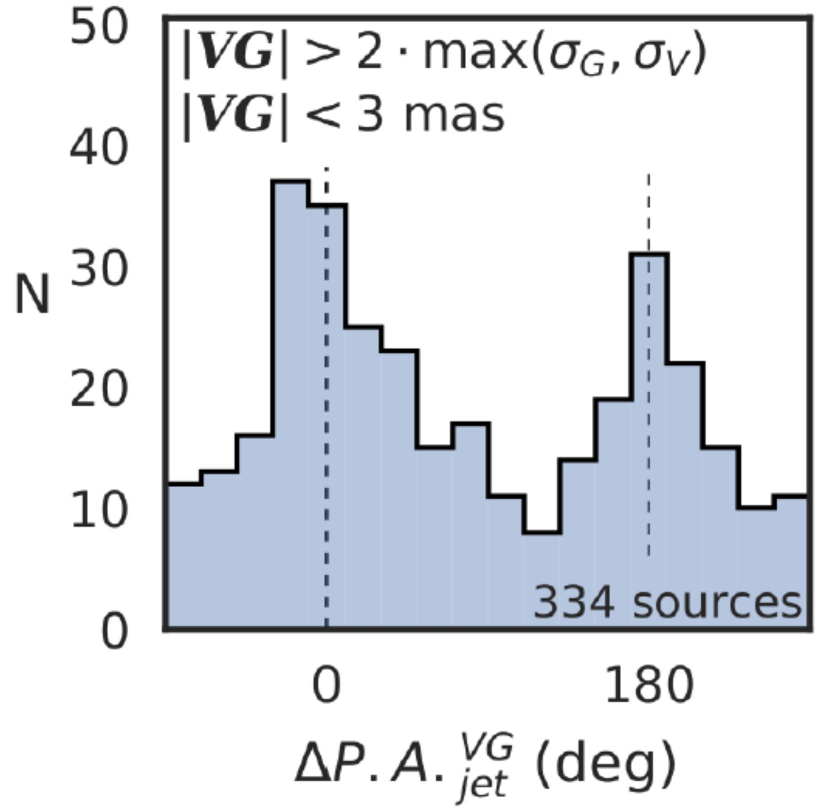
1418+546 1514+192 1546+027

Credit: SDSS

- Optical structure: The host galaxy may not be centered on the AGN or may be assymmetric.
- Optical systematics unknown, fraction of millarcsecond optical centroid offset?
- Optical imaging generally 10s of milliarcsecond. In general, no sub-mas optical imaging.

Optical vs. Radio systematics offsets





Petrov & Kovalev (MNRAS, 2017) show that optical-radio astrometric offsets Correlate with jet direction (or anti-direction).

They argue that the offsets are dominated by optical synchrotron jets.

Optical vs. Radio systematics offsets

Petrov & Kovalev (MNRAS, 2017)

- Example of optical jet in “nearby” 3C 264 would scale to ~milli-arsecond offsets at typical AGN distances.

- Optical synchrotron jets may be limiting factor in radio-optical astrometric agreement.

- VLBI interferometry “locks” onto the brightest component. Also extremely high resolution resolves out extended structures. So VLBI positions is close ot the core.

- Gaia optical image’s centroid averages all of the light distribution, jet included. “Beam” is 60 milliarcseconds.

- Optical may be more easily biased than radio.

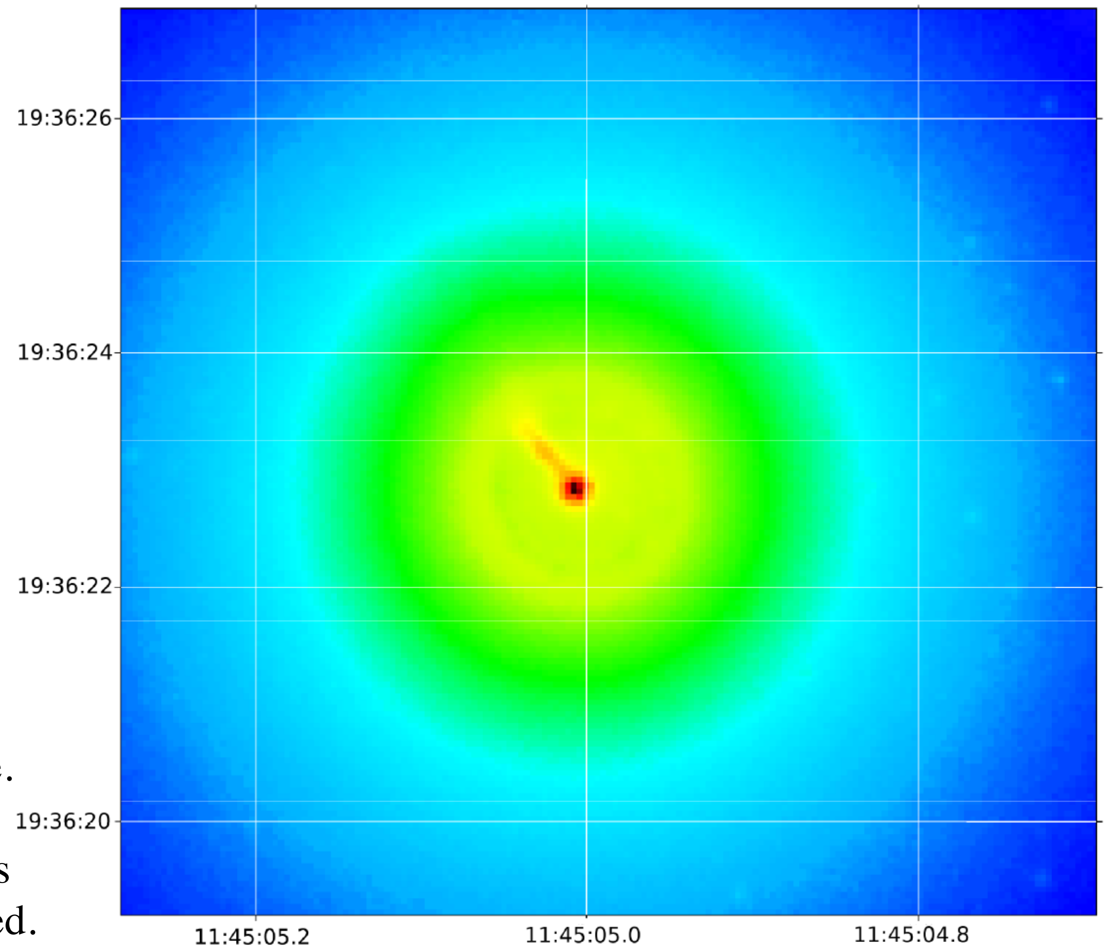


Figure 3. The archival HST image of 3C264 at 606 nm, HST project ID 13327 (Meyer et al. 2015).

Optical vs. Radio positions

Positions differences from:

• Astrophysics of emission centroids

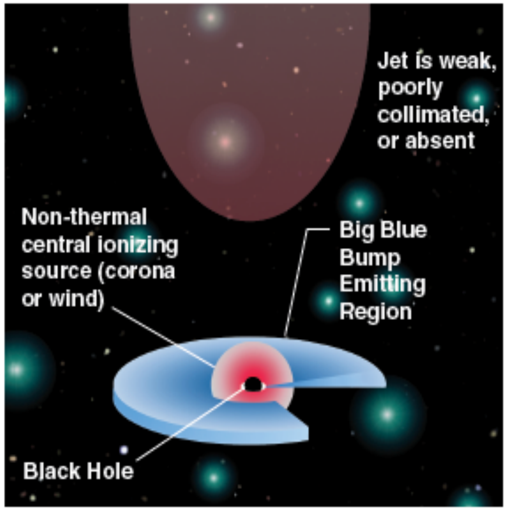
- radio: synchrotron from jet

- optical: synchrotron from jet?
  non-thermal ionization from corona?
  big blue bump from accretion disk?

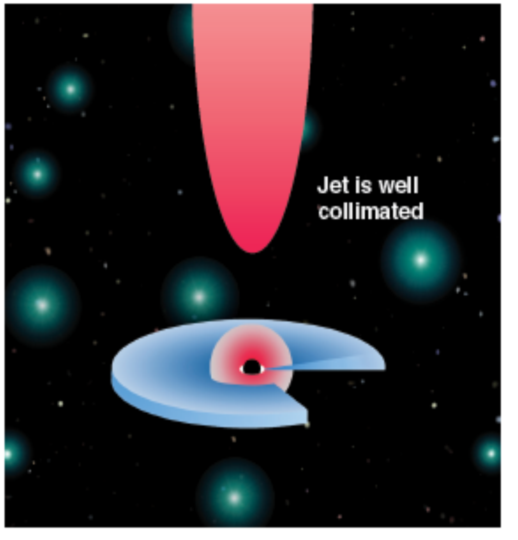
• Instrumental errors both radio & optical

• Analysis errors

Radio-quiet Quasar

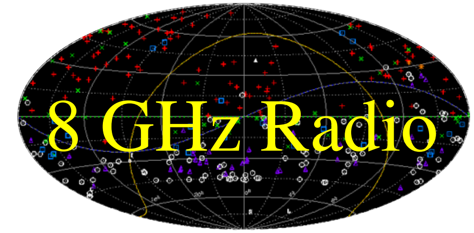


Radio-loud Quasar

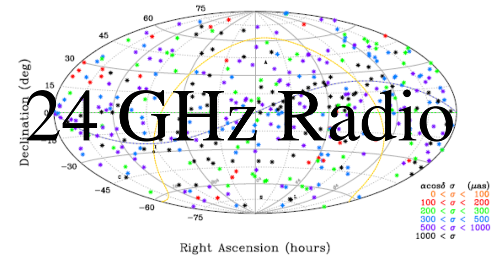


Credit: Wehrle et al, μas Science, Socorro, 2009
http://adsabs.harvard.edu/abs/2009astro2010S.310W

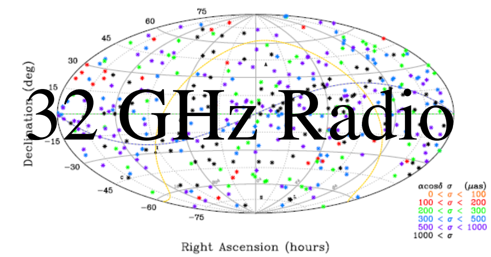
Summary: Tying Optical & Radio



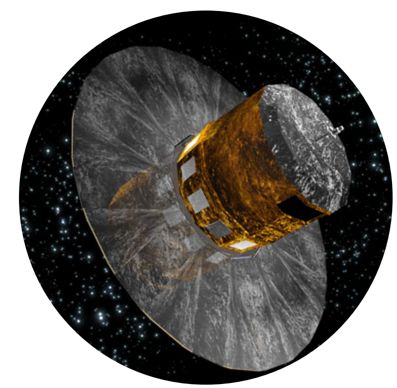
- **Goal:** Tie of optical and radio celestial frames for deep space navigation and astronomical applications.



- **Roadmap:**
  - Preliminary optical & radio data are in-hand.
  - Increase number of sources in common between optical and radio
  - Expect to be limited by systematic calibration errors
  - Quantify and reducing systematics by
    - getting data in three radio bands (8, 24, 32 GHz)
    - Compare independent analysis chains
    - Image sources in radio to quantify non-pointlike structure



- **Preliminary results: Gaia DR1-aux vs. VLBI**
  - Excellent 3-D tie precision of ~ 20 μas.
  - Random scatter ~ 400 to 500 μas limited by Gaia statistical error
  - Accuracy limited by systematic errors at 100 – 500 μas.
  - SX (8 GHz) on low end ~100 μas. K (24) Ka (32) 200-500 μas.
  - Hints that 24 and 32 GHz VLBI are cleaner than 8 GHz
  - K and Ka lower percentage outliers, smaller scatter vs Gaia
  - Control of VLBI systematics will require increased southern observations.



Gaia Optical